MPGD Trackers in the ePIC Detector at the EIC

Kondo Gnanvo

Radiation Detectors & Imaging Group (RD&I Group), Jefferson Lab, Virginia

On behalf of the ePIC Collaboration

Coordinating Panel for Advanced Detector Workshop (CPAD2024) – Nov. 18 - 22, 2024 University of Tennessee, Knoxville

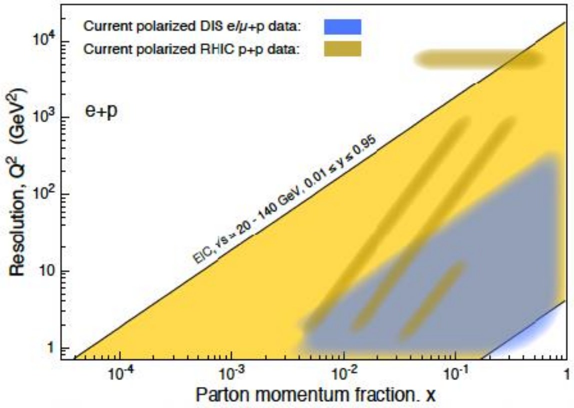
Outline

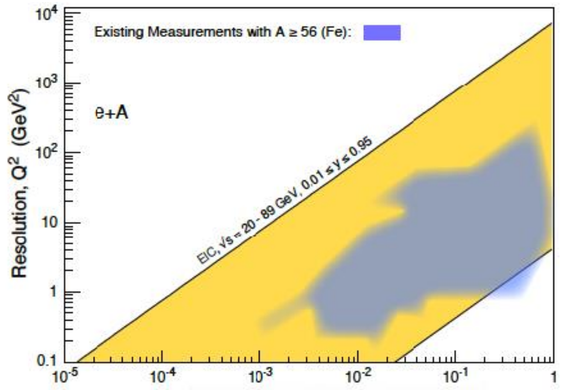
- Overview of the MPGD Subsystems in the ePIC Central Tracker
- The μRWELL Barrel Outer Tracker (μRWELL-BOT)
- The Cylindrical Micromegas Barrel Inner Layer (CyMBAL)
- The μRWELL End Cap Trackers (μRWELL-ECT)
- ePIC MPGD SALSA Readout Electronics

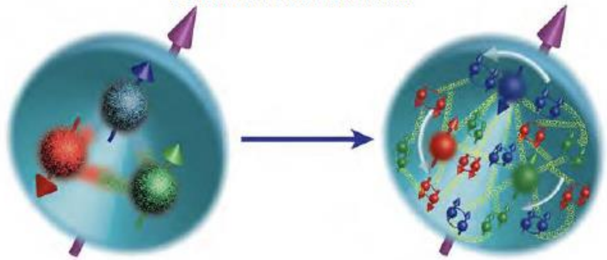
The Electron Ion Collider (EIC) @ BNL

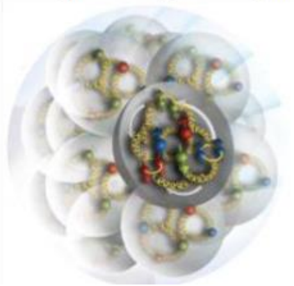
EIC is the flagship Nuclear Physics (NP) Facility in the US (2031+)

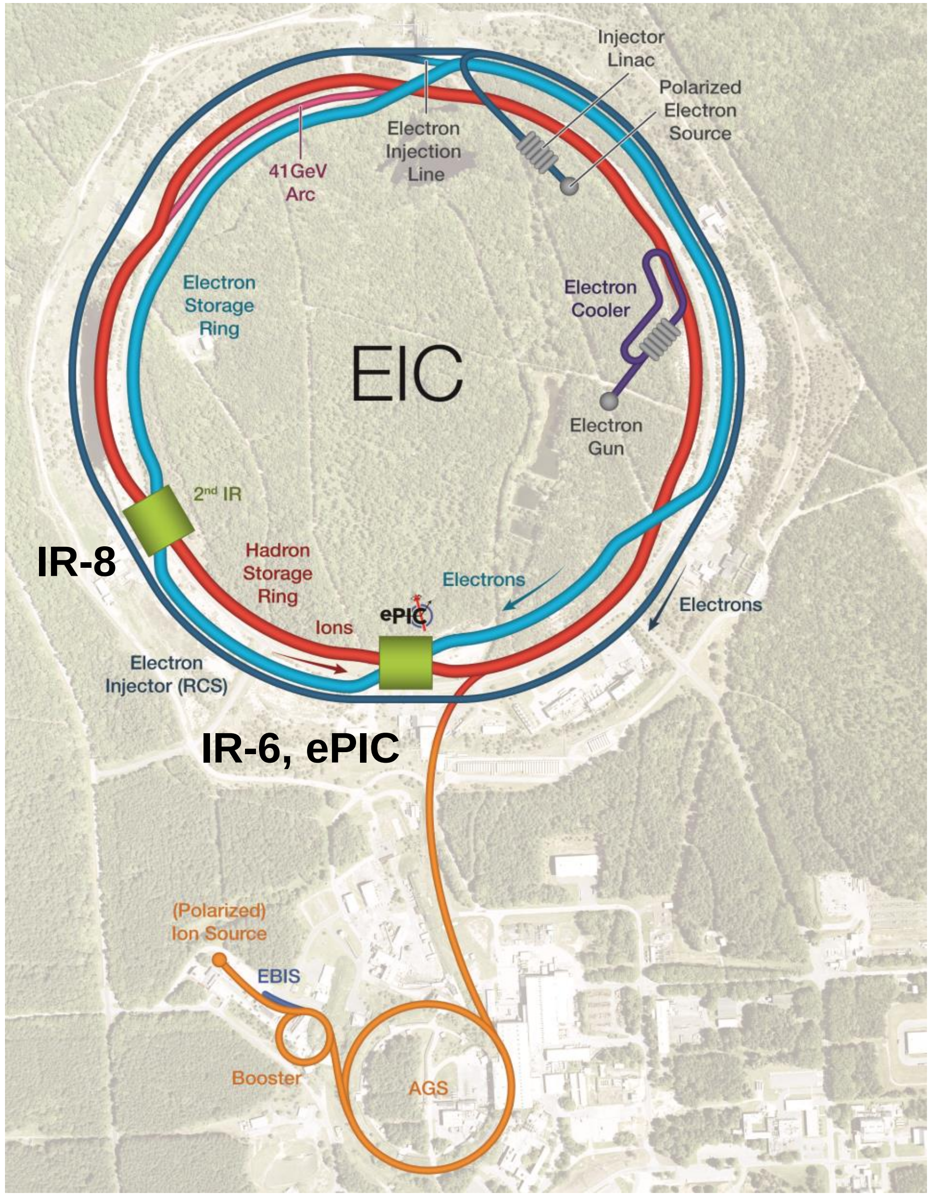
- **High Luminosity:** L= $10^{33} – 10^{34} cm^{-2}sec^{-1}$, 10 – 100 fb^{-1}/year
- **Highly Polarized Beams:** 70%
- **Large Center of Mass Energy Range:** E_{cm} = 20 – 140 GeV
- **Large Ion Species Range:** Protons – Uranium
- **Particle production rate:** ~5 @ 500 kHz
- **ePIC Detector:** Large Acceptance and Good Background Conditions











Electron-Proton (and) Ion Collider Detector (ePIC) @ EIC

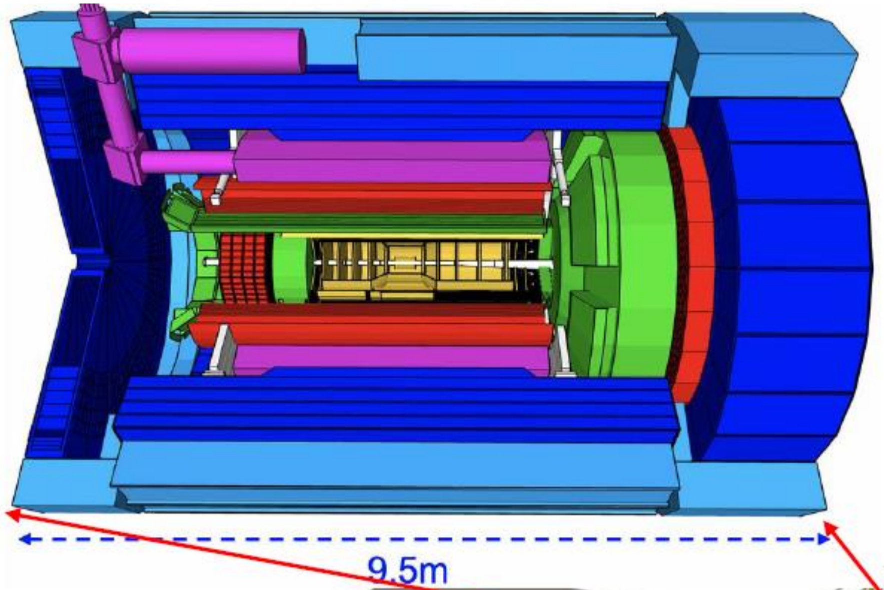
Vertexing and Tracking:
- Silicon Vertex Tracker (MAPS)
- MPGD (µRWELL/µMegas)

Particle Identification:
- TOF (AC-LGAD also for tracking)
- pfRICH (Aerogel/HRPPD)
- hpDIRC (Quartz/MCP-PMT)
- dRICH (Aerogel+C_2F_6/MCP-PMT)

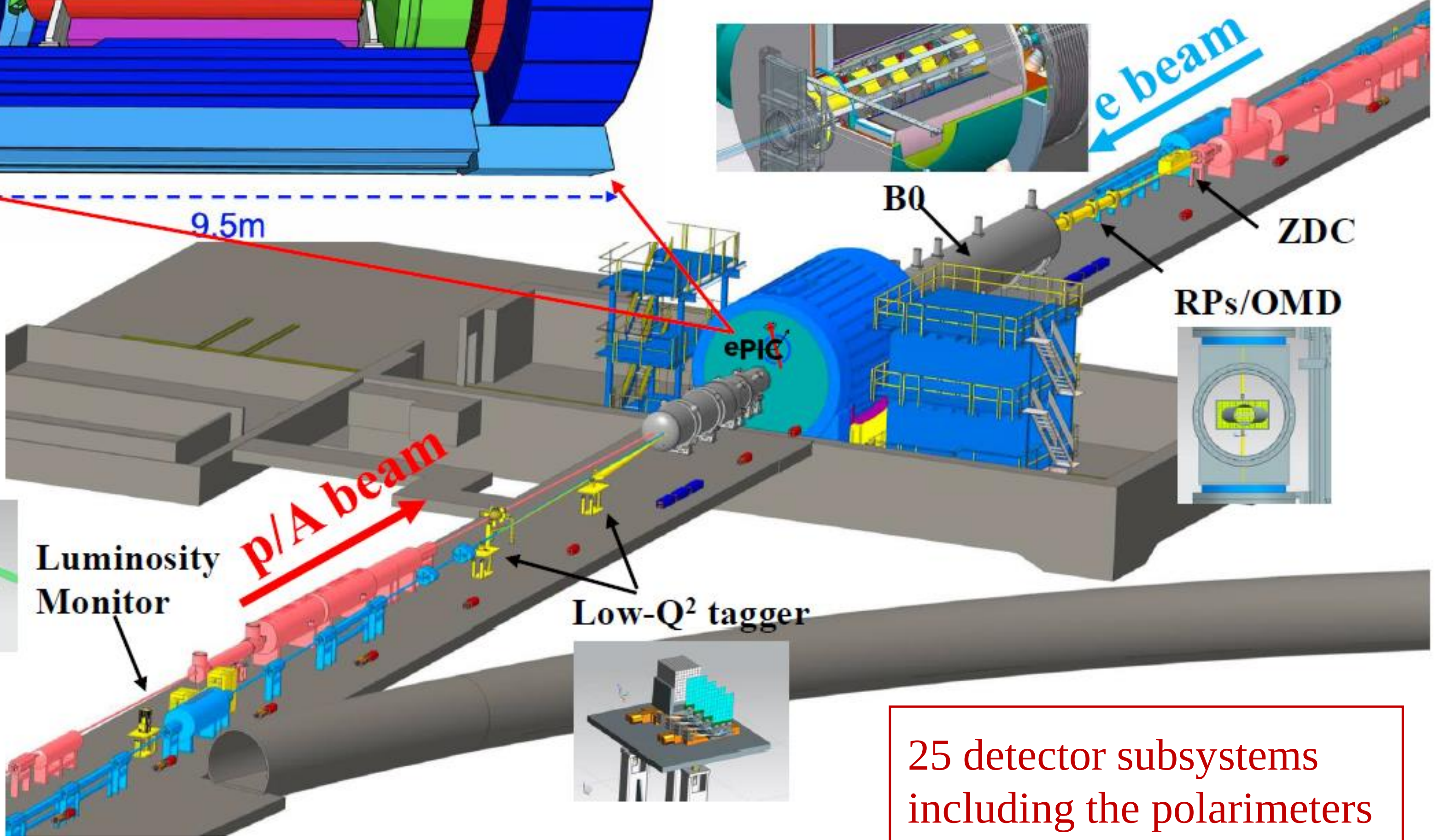
EM Calorimeters:
- EEMCal ($PbWO_4$/SiPM)
- Barrel EMCal (Pb+SciFi/SiPM) with imaging layers (Pb+SciFi/AstroPix)
- FEMC (W+SciFi)

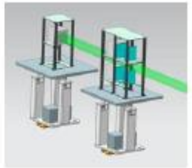
Hadronic Calorimeters:
- Backward HCAL (Fe+Sc/SiPM)
- Barrel HCal (sPHENIX re-use)
- LFHCAL (Fe+Sc&W+Sc/SiPM)

Far-Backward:
- Luminosity monitor (AC-LGAD, W+SciFi)
- Low-Q^2 tagger (Si/Timepix4)



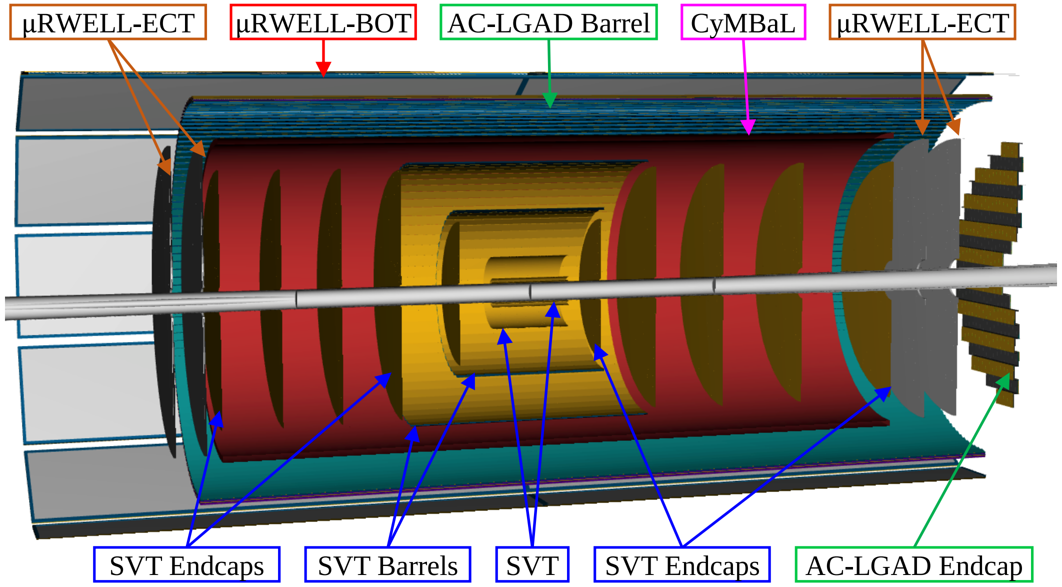
Far-Forward:
- Roman Pots (AC-LGAD)
- B0 Magnet Spectrometer (AC-LGAD, $PbWO_4$)
- Off-Momentum Detector (AC-LGAD)
- Zero Degree Calorimeter ($PbWO_4$, Fe/SiPM)





25 detector subsystems including the polarimeters

ePIC Central Tracking Detectors - Requirements & Performances



Silicon Vertex Tracker (SVT): ~6 μm point resolution

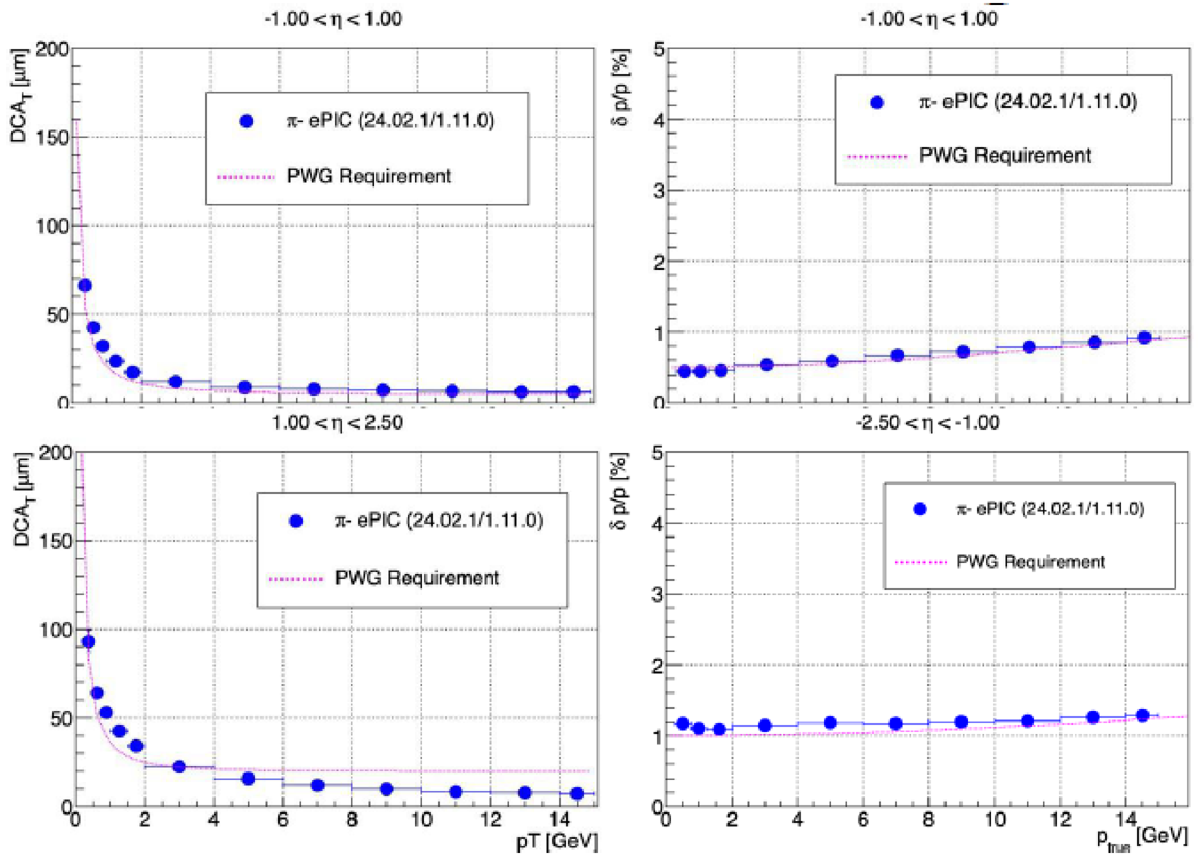
- 3 inner barrels: ITS3-curved wafer-scale sensor, 0.05% X/X0
- 2 outer barrels: ITS3-based sensors (EIC-LAS), 0.25/0.55% X/X0
- 5 disks (forward/backward), EIC-LAS, 0.25% X/X0

AC-coupled LGAD TOF: 30 μm + 30 ps resolutions

- Barrel TOF: 0.05 x 1 cm strip, 1% X/X0
- Forward TOF: 0.05 x 0.05 cm pixel, 5% X/X0

Micro Pattern Gaseous Detectors (MPGD): 10 ns & 150 μm resolutions

- **2 × 2 End cap disks:** GEM-μRWELL hybrid detectors
- **One inner barrel layer:** Cylindrical Micromegas
- **One outer barrel layer:** Thin-gap GEM-μRWELL hybrid detectors



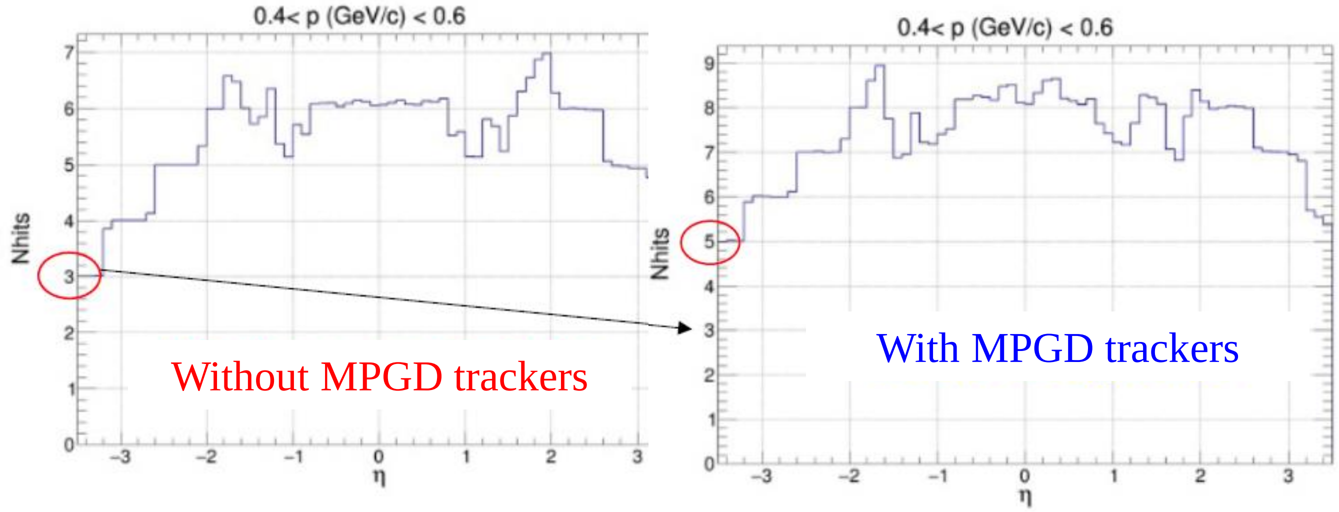
Rapidity Range	Momentum Resolution	Spatial Resolution
Backward (-3.5 to -2.5)	$\sim 0.10\% \times p \oplus 2.0\%$	$\sim 30/pT\ \mu m \oplus 40 \mu m$
Backward (-2.5 to -1.0)	$\sim 0.05\% \times p \oplus 1.0\%$	$\sim 30/pT\ \mu m \oplus 20 \mu m$
Barrel (-1.0 to 1.0)	$\sim 0.05\% \times p \oplus 0.5\%$	$\sim 20/pT\ \mu m \oplus 5 \mu m$
Forward (1.0 to 2.5)	$\sim 0.05\% \times p \oplus 1.0\%$	$\sim 30/pT\ \mu m \oplus 20 \mu m$
Forward (2.5 to 3.5)	$\sim 0.10\% \times p \oplus 2.0\%$	$\sim 30/pT\ \mu m \oplus 40 \mu m$

3 MPGD subsystems in ePIC Central tracking detectors:

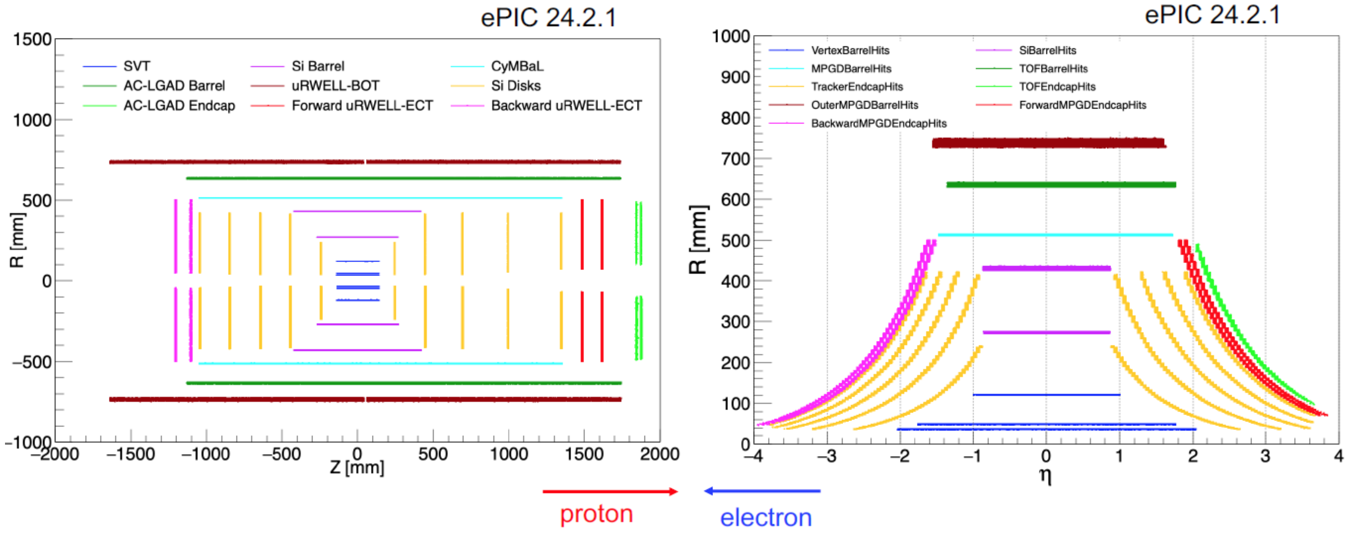
- CyMBAL: Barrel Inner Cylindrical Micromegas Layer
- µRWELL-BOT: Barrel Outer MPGD tracker
- µRWELL-ECT: End cap MPGD disks

MPGD tracking detectors in ePIC central region aim at complementing the Si trackers to provide

- Fast timing (10 ns) for pattern recognition
- additional space points (< 150 µm) for pattern recognition and help improve angular resolution at the hpDIRC level

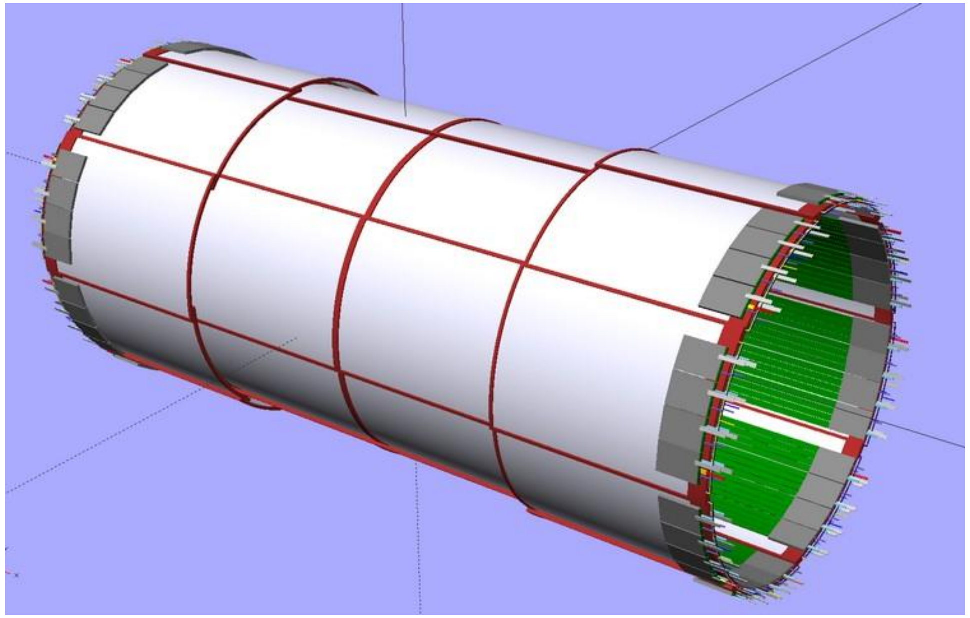


- GEANT-level tracker hits showing geometric coverage

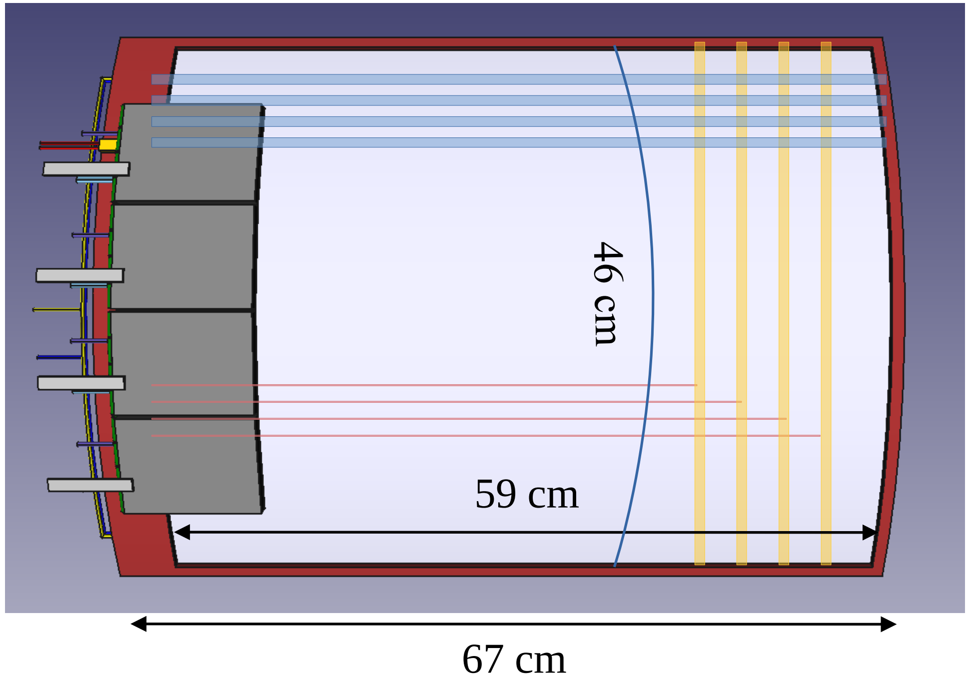


Cylindrical Micromegas Barrel Layer (CyMBAL)

CyMBaL layout in ePIC



CyMBAL module design



Requirements:

- Spatial resolution ~150μm
- Time resolution ~10ns
- Light, less than 1% X0
- Hermetic
- Tight space: ~5cm in R
- Magnetic field: ~2T

Detector layout:

- 32 modules: 8 modules in ϕ × 4 modules in z
- Full overlaps in ϕ and in z for hermeticity
- 1024 readout channels/module
- 32K readout channels

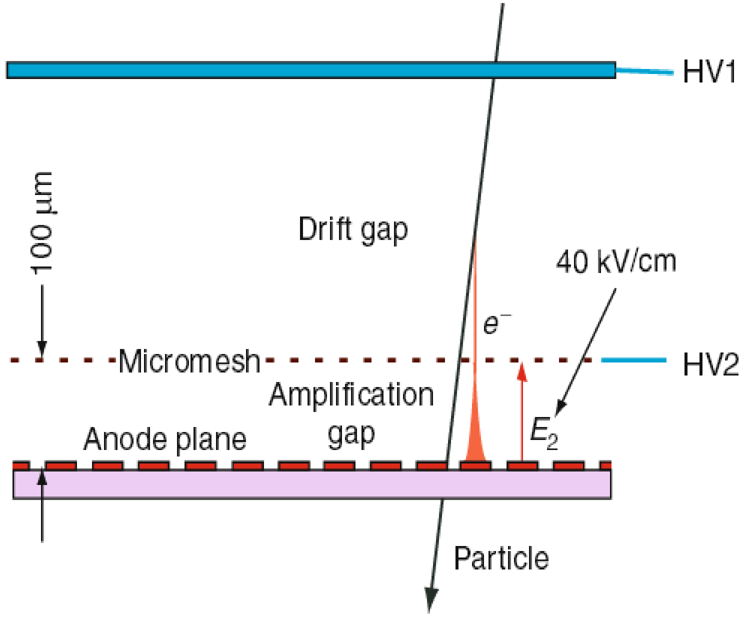
Module dimensions

- Z = 67 cm
- R*phi = 48 cm

Active zone dimensions

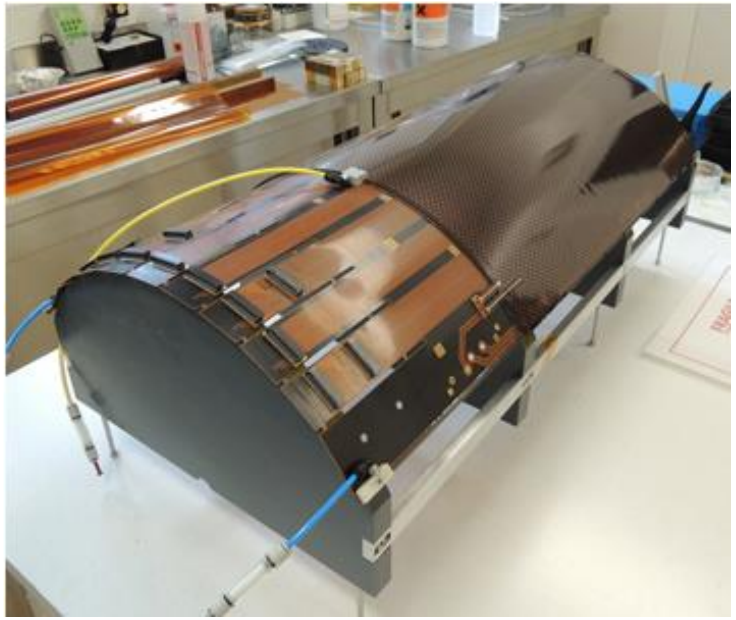
- Z = 59 cm
- R*phi = 46 cm

CyMBAL – Micromegas technology



[Y. Giomataris, NIMA 419 (1998) 239]

Curved CLAS12 MVT module



Material budget ~0.4%

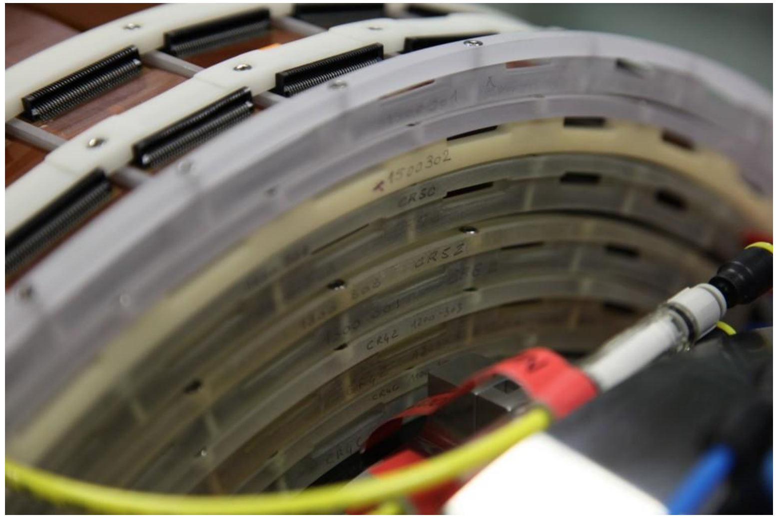
CLAS12 Micromegas Vertex Tracker (MVT) @ JLab

- ❖ Resistive Micromegas technology
- ❖ High radiation environment @ B = 5T
- ❖ Taking data since 2017

Upgrade for CyMBAL modules:

- ❖ Larger size modules
- ❖ 2D strip readout

CLAS12 MVT: 6 layers fit in tight space

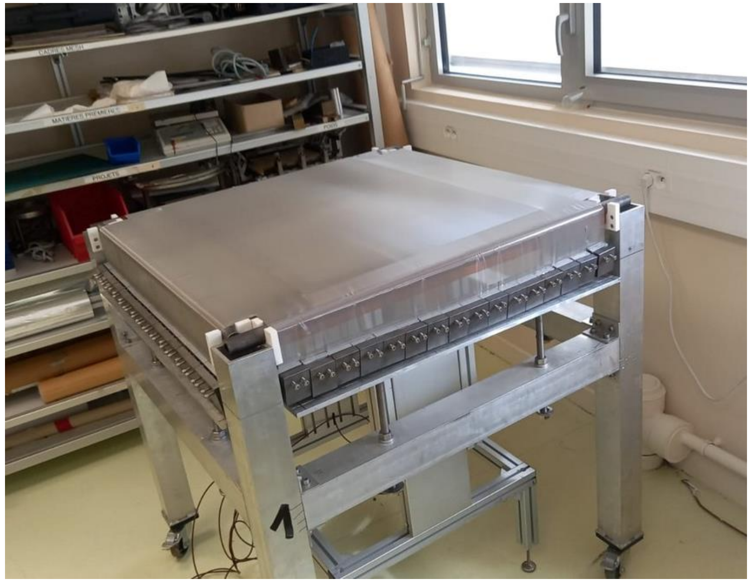


Ongoing R&D effort: Analysis of the 2023 & 2024 test beam data on the 2D prototypes

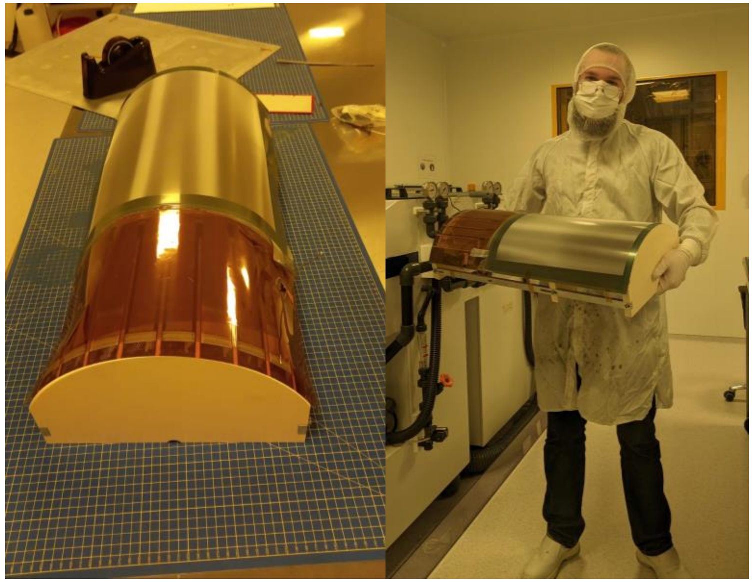
- ❖ Complete the tests on resistive patterns and 2D readout with new prototypes
- ❖ Design & production of arge scale prototype with 2D readout using CLAS12 mechanics
- ❖ Mechanical mock-up for a scale 1:1 prototype
- ❖ Test performance of a small 2D prototype with a 1mm drift gap with different gas

CyMBAL module: Toward a scale 1:1 prototype

Mesh tensioning system: it allows us to reach low tension values

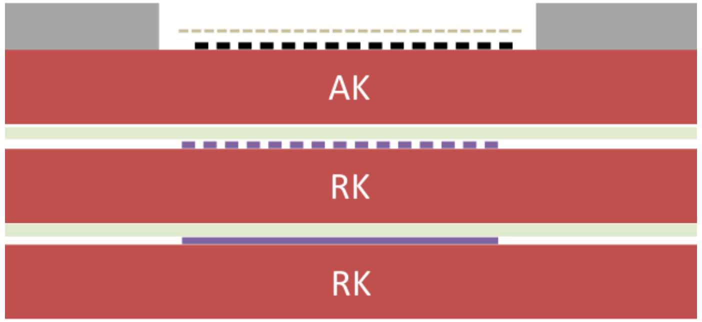


- Bulk of a resistive CLAS12 PCB
- Bent in shape



Low material budget: Achieved by stretching flexible PCB on a carbon frame

Mesh – resistive layer



R/O flexible PCB (Kapton)

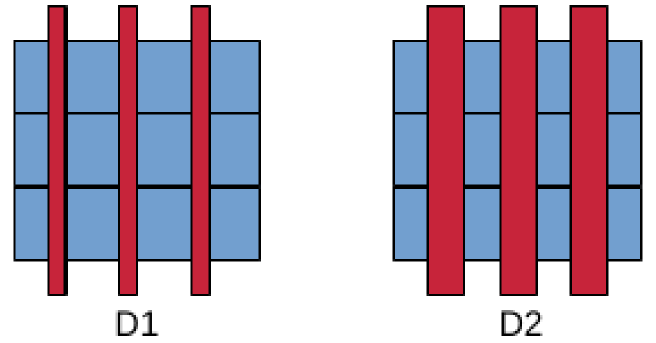
Photo-resistive material:

- ❖ Pyralux out of production
- ❖ Switched to Vacrel (was used in the past)
- ❖ Difference film thickness (from 64 µm to 50 µm)
- ❖ Difference in composition:
  - ▪ Check adherence
  - ▪ Adjustments of the development stage
- ❖ Tests with 40x40cm2 detectors ongoing

CyMBAL - Ongoing R&D

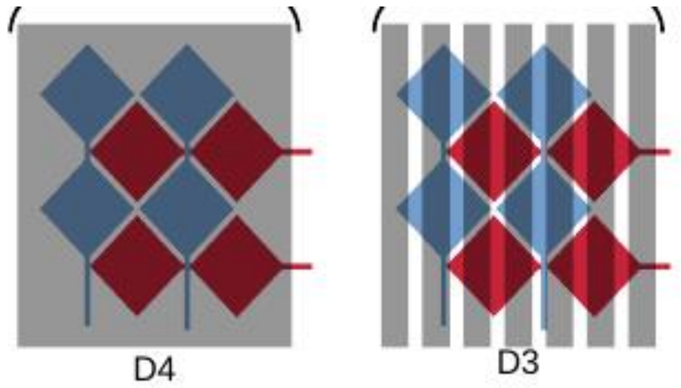
Several 12 cm × 12 cm low material budget (0.2% X0) micromegas prototypes tested with various R/O pattern and resistive motifs

Straight strips

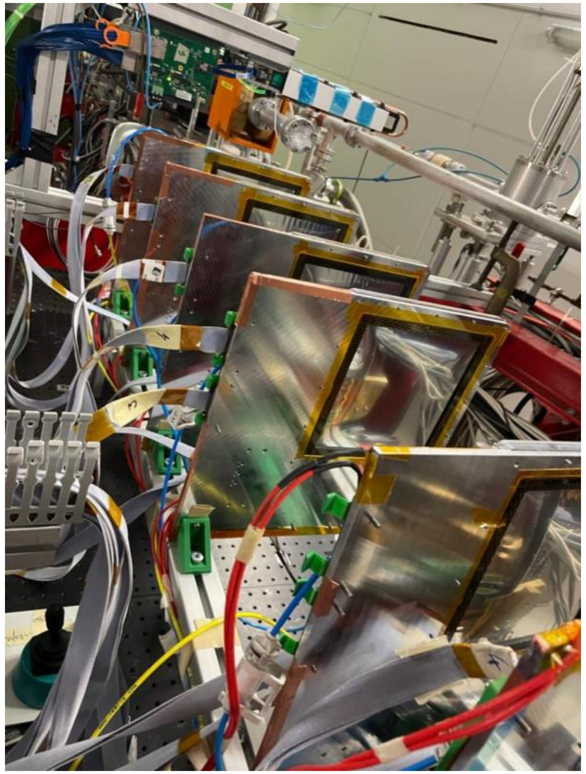


- D1: pitch from 0.5 to 1.5 mm, interstrip 25%
- D2: pitch 1 mm, interstrip 50%
- Resistive layer: full, resistivity ~10MΩ/□

ASACUSA strips

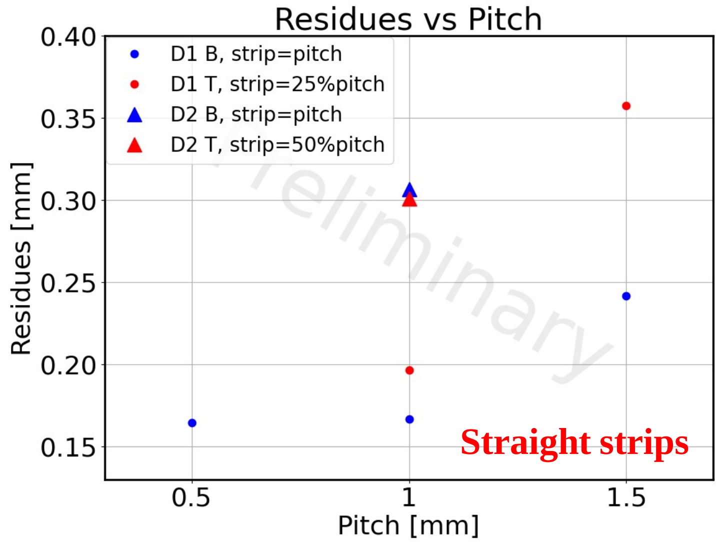


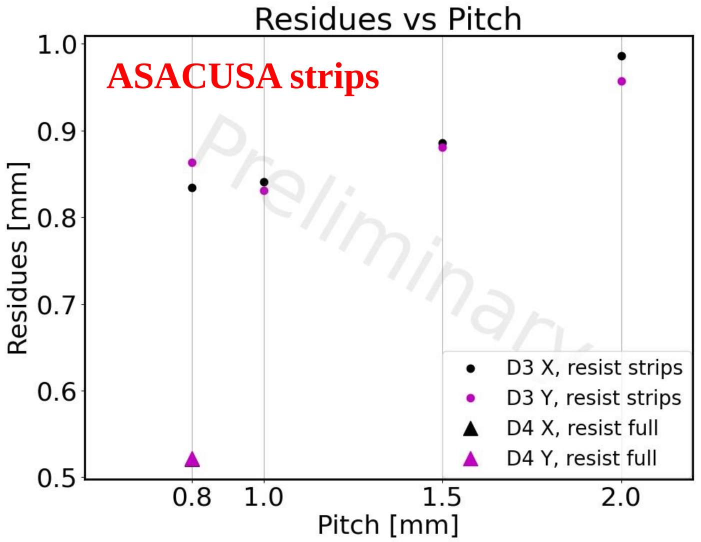
- D3: resistive strips of 500μm pitch
- D4: full layer with resistivity ~500kΩ/□



MAMI beam test (June 2023)

- 880 MeV electron beam
- ALPIDE-based reference telescope
- Important multiple scattering effect
- Geant4 simulations to cross check

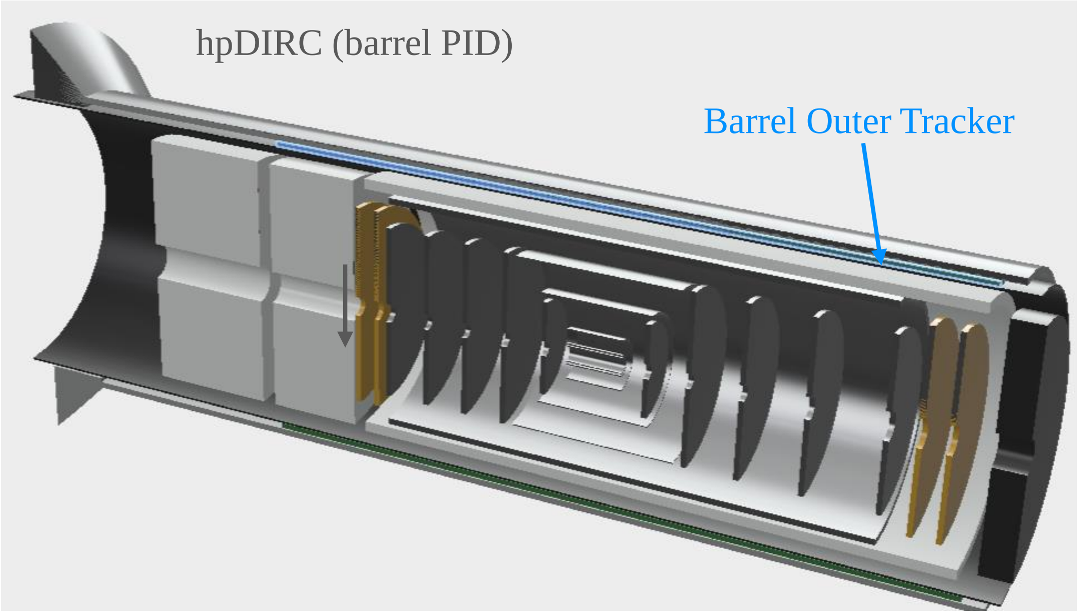




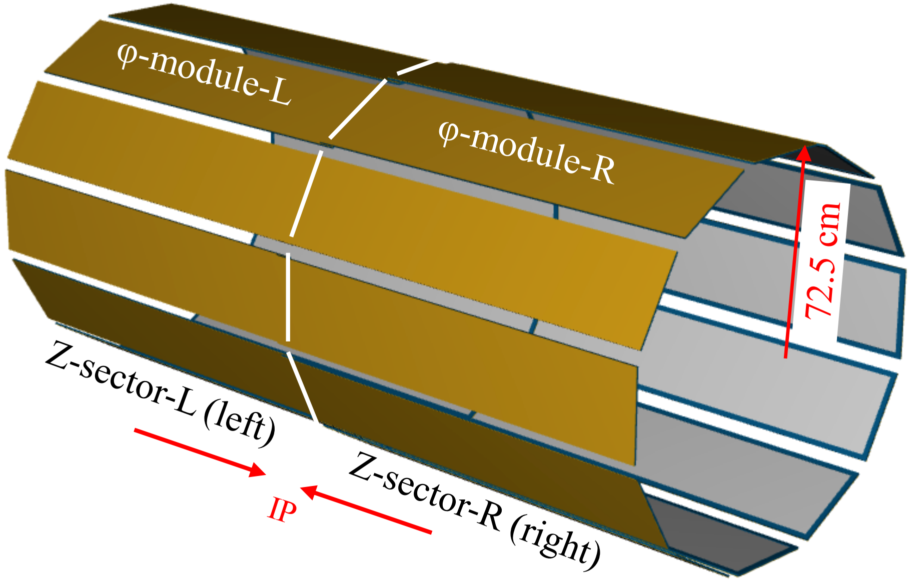
ePIC Barrel Outer MPGD Layer - µRWELL-BOT

µRWELL-BOT Layout

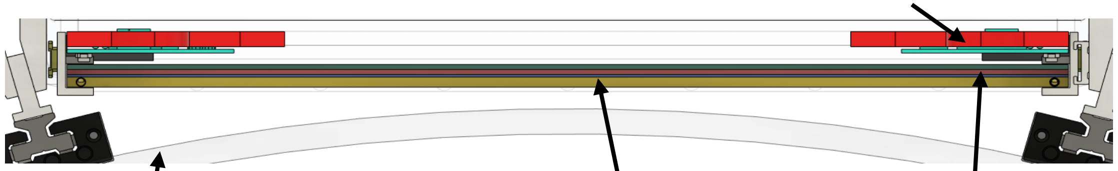
- L = 340 cm (−165 cm ≤ Z ≤ 175 cm), R = 72.5 cm
- 24 modules in 12-sided polygon shape trackers
  - Segmented into 12 sectors along φ
  - 2 modules (left & right) per sector along **z**
- Fast timing layer ~ 10 ns
- Radiation length < 2% in active area



µRWELL-BOT Tracker in ePIC central detector

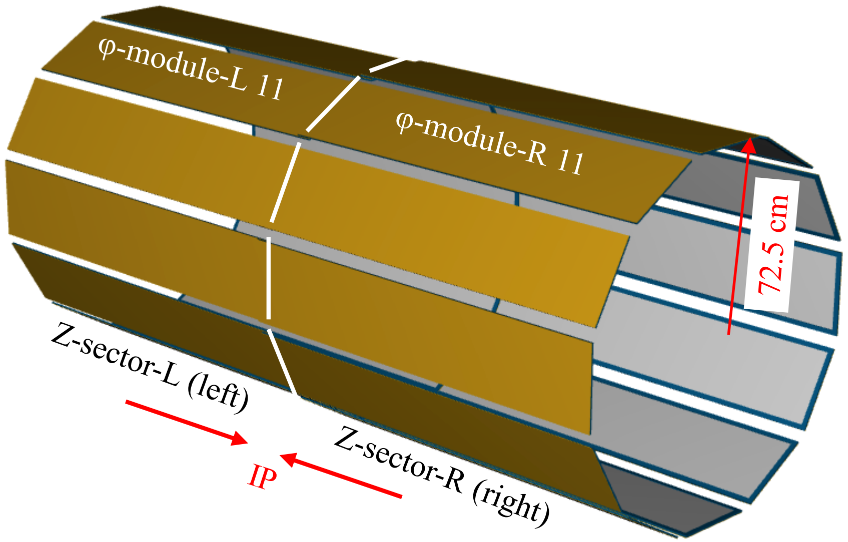


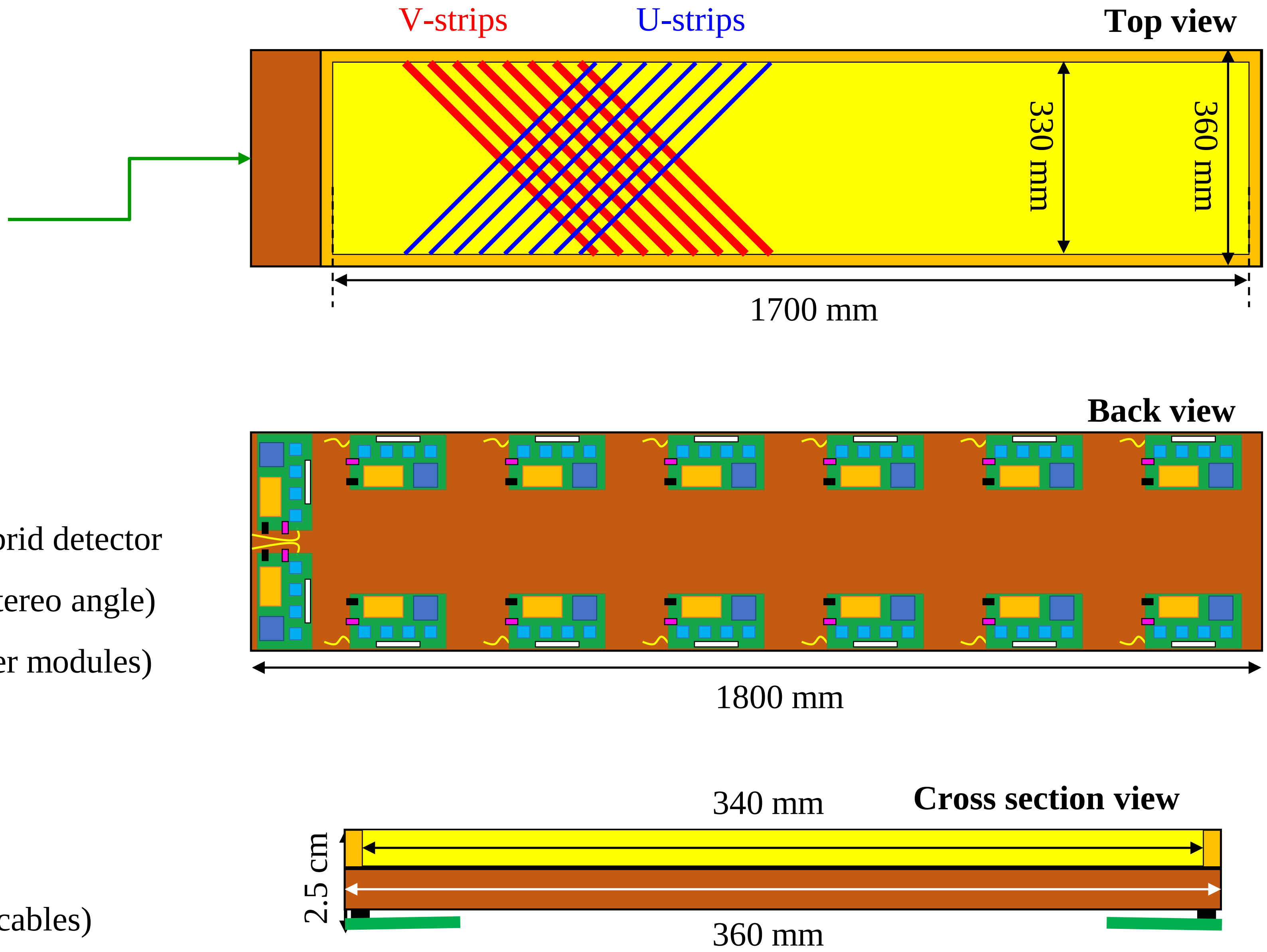
µRWELL-BOT layer in dodecagon shape



Front view of µRWELL-BOT module

µRWELL-BOT module layout





µRWELL-BOT module

- Thin-gap double amplification GEM-µRWELL hybrid detector
- Capacitive-sharing U-V strips readout layers(45^{O} stereo angle)
- Pitch: 1.14 mm (1790 U-strips and 1790 V-strips per modules)

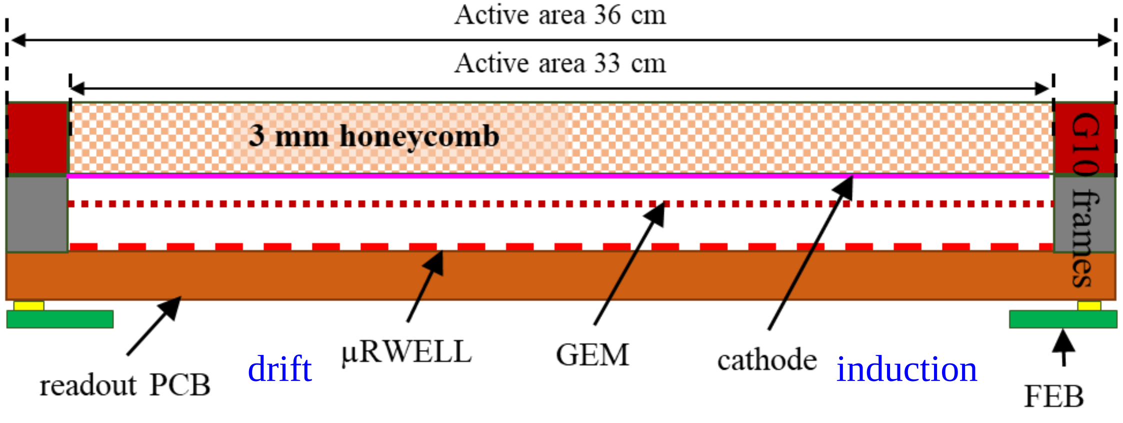
On-detector Front End Boards (FEBs)

- Based on SALSA electronics
- 14 FEBs / modules
- Direct connection on the back of modules (no flex cables)

Thin-gap GEM-µRWELL hybrid - R&D and prototyping

3 critical components of thin-gap MPGDs:

- **Thin gap drift:** 1 mm gas gap in the ionization region
  - Improve both spatial and time resolution
  - Reduce E × B effect
- **Double amplification:** High gain & stable detector operation
  - Hybrid amplification ➔ GEM pre-ampl. + µRWELL for 2nd ampl.
  - Compensate for ionization charges loss in the thin gap
- **Capacitive-sharing structures:** Coarse pitch / Excellent spatial resolution
  - Versatile readout pattern (U / V, X / Y, zigzag strips …)
  - K. Gnanvo, NIM A1047, 167782 (2023)

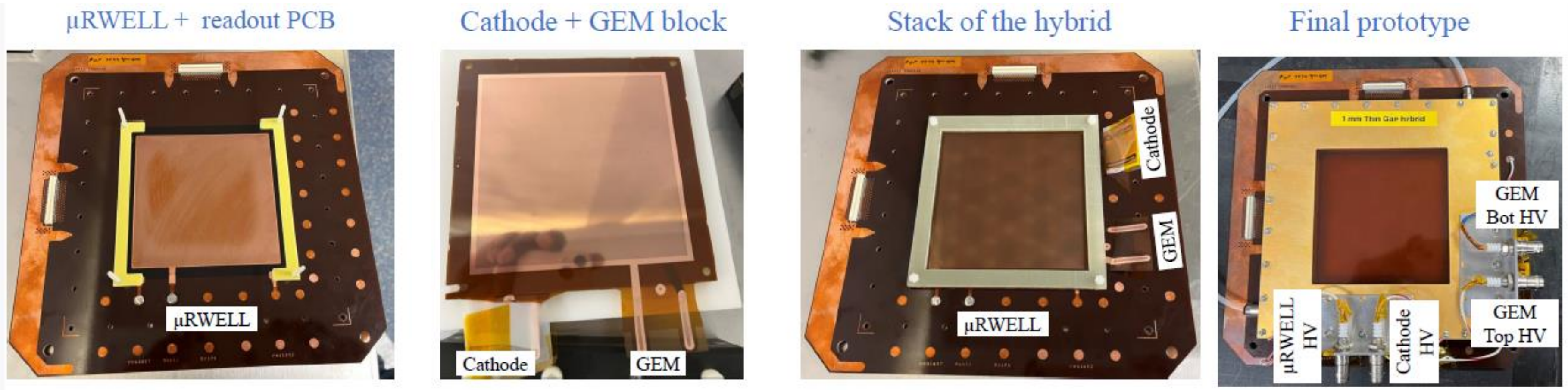


cross-section view of thin-gap GEM-µRWELL detector

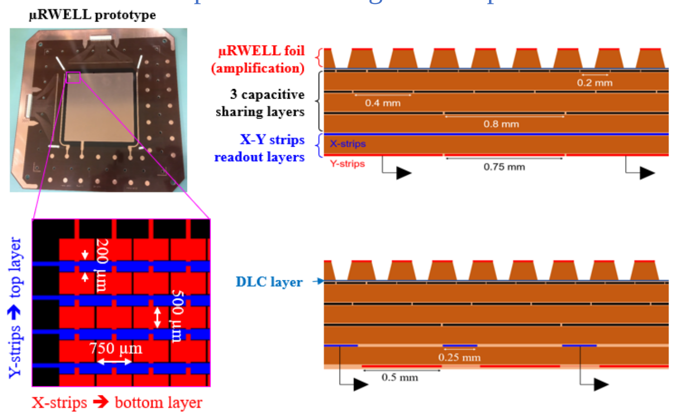
https://indico.jlab.org/event/751/contributions/13585/attachments/10462/15726/20231031_EICGENRD16_ThinGapMPGD_KG.pdf

https://www.jlab.org/sites/default/files/eic_rd_prgm/files/2023_Proposals/20230714_eRD_tgMPGD_Proposal_FY23_Final_EICGENRandD2023_16.pdf

Assembly of small (10 cm × 10 cm) thin-gap GEM-µRWELL hybrid detector



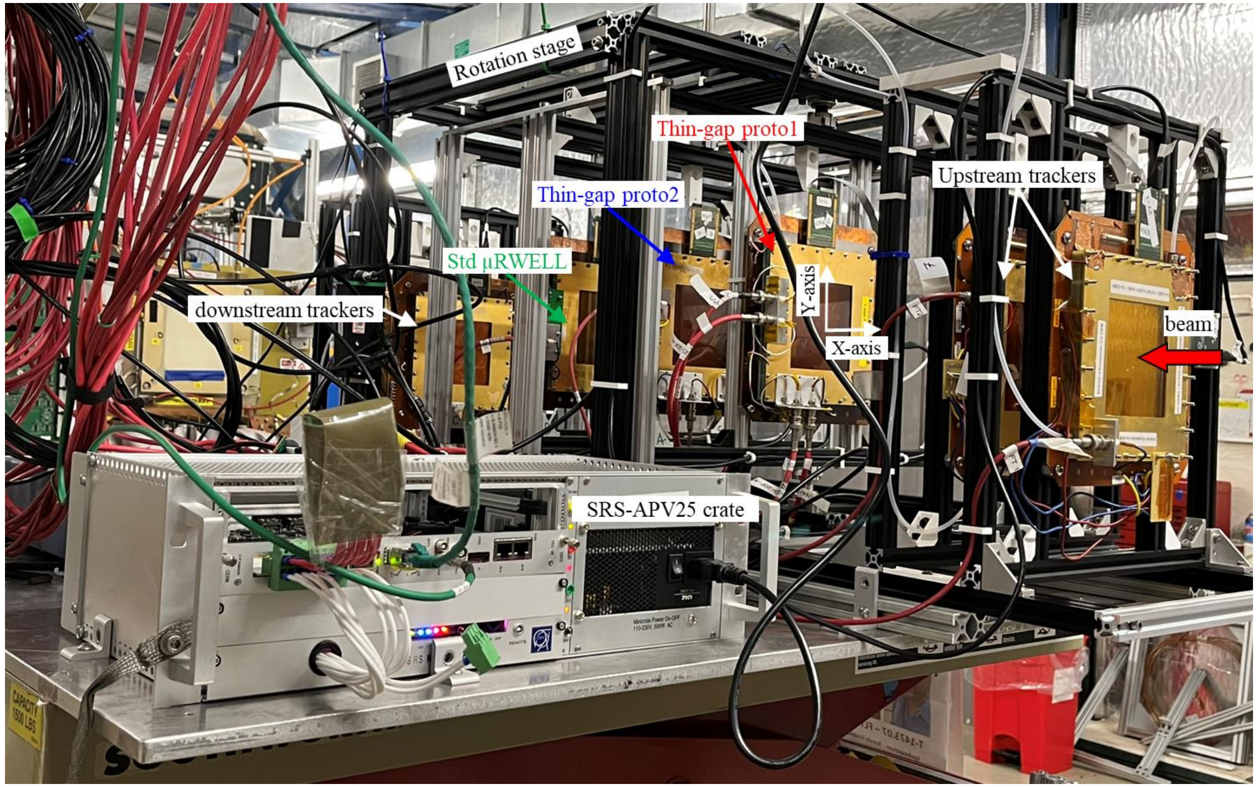
Capacitive-sharing X-Y strip readout



Thin-gap GEM-µRWELL hybrid detector: Proof of concept

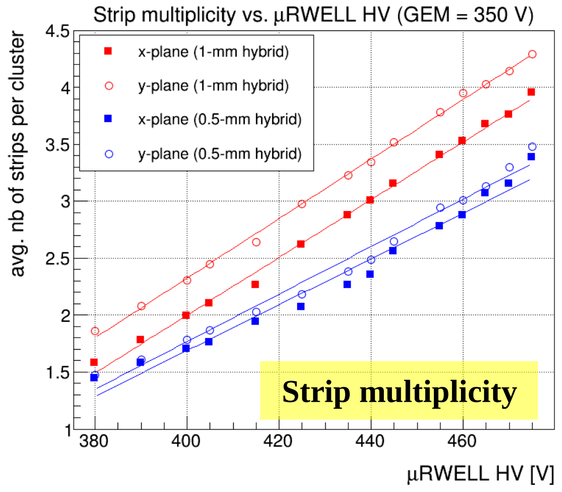
Performance in beam of thin-gap GEM-µRWELL hybrid (FNAL 2023)

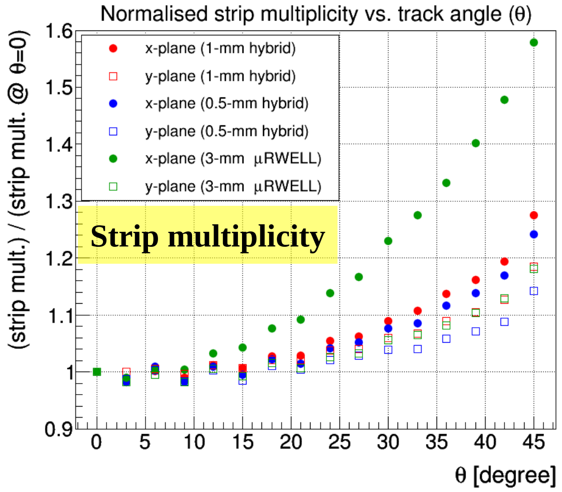
- ~10 small thin-gap MPGD prototypes tested
  - All 3 MPGD technologies: GEM, µRWELL, Micromegas tested
- 2 thin-gap GEM-µRWELL hybrid & 1 standard gap prototypes
  - 0.5-mm tin-gap, 1-mm thin-gap & 3-mm std-gap

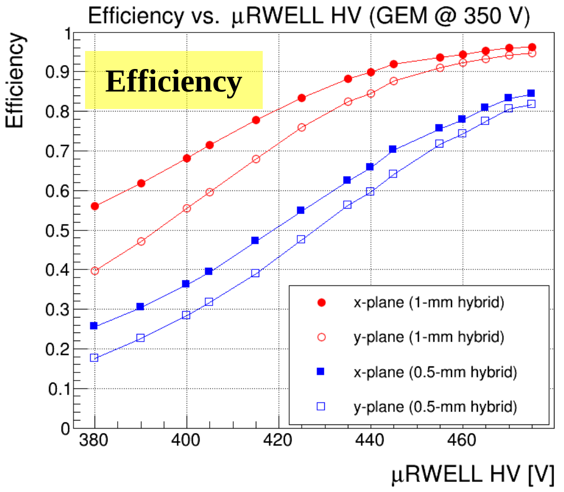


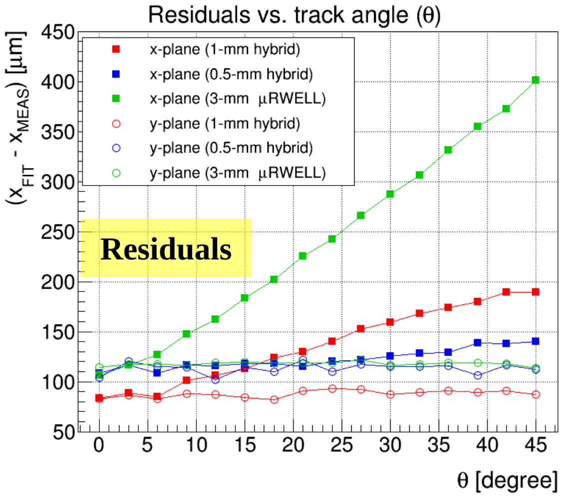
Beam test setup

Space resolution < 150 µm & efficiency > 92% on for 1-mm prototype (red) - track angle range of between 0 – 45 degrees



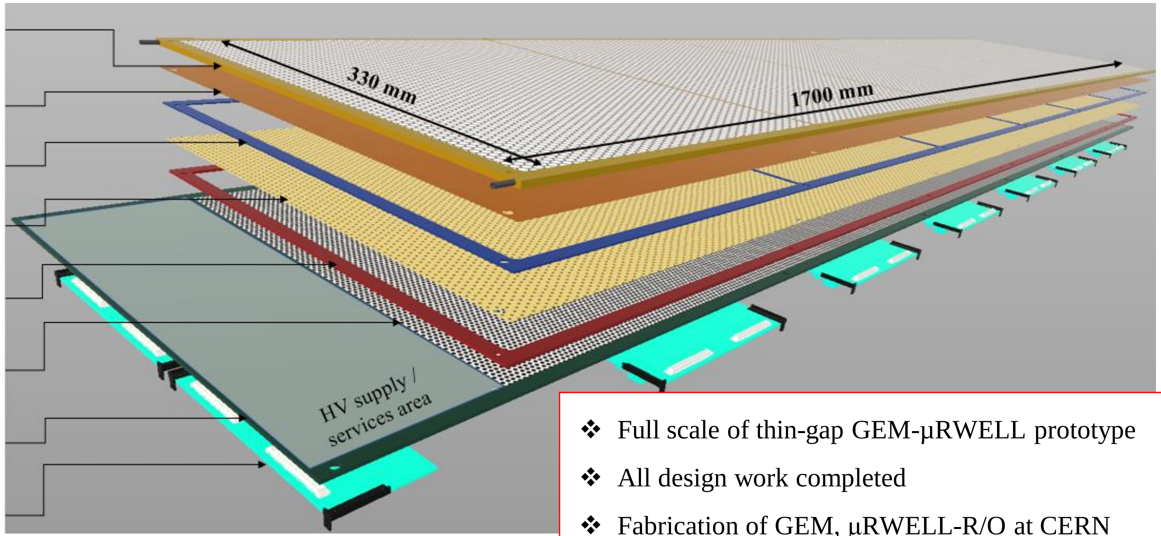






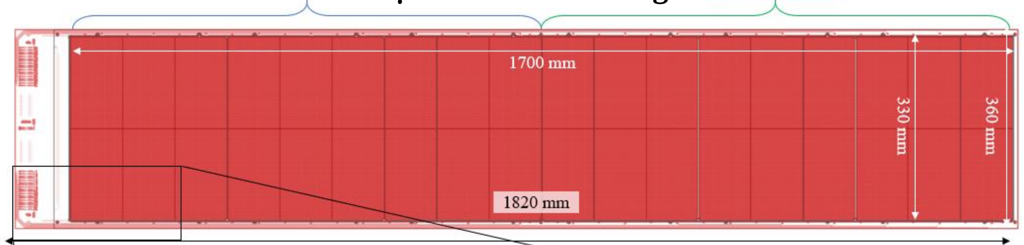
µRWELL-BOT module: Design of full scale engineering test article

CAD design of thin-gap GEM-µRWELL engineering test article



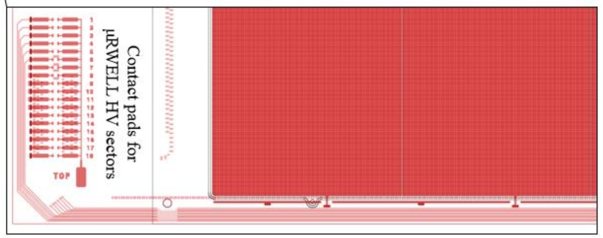
- ❖ Full scale of thin-gap GEM-µRWELL prototype
- ❖ All design work completed
- ❖ Fabrication of GEM, µRWELL-R/O at CERN
- ❖ Assembly and test at JLab ➔ second half off 2025

µRWELL foil Design



µRWELL dimension

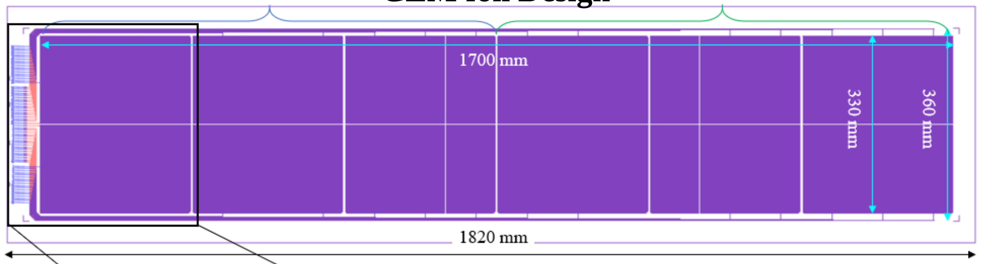
- ❖ **Overall:** 1820 mm × 360 mm
- ❖ **Active area:** 1700 mm x 330 mm



Two of the 36 µRWELL sectors

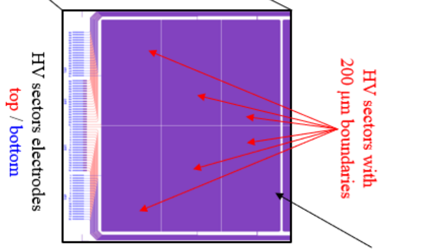
- ❖ The active area of 36 HV sectors (180 mm× 96 mm) similar to the HV sectors separated by 100 µm dead area
  - ❖ The 18 sectors on the left side have normal segmentation
  - ❖ The 18 on the right have a random segmentation ➔ Study impact on detector efficiency
- ❖ All 36 HV sectors connections are made on the left side of the GEM foil

GEM foil Design



Foil dimension

- ❖ Total: 1820 mm × 360 mm
- ❖ Active area: 1700 mm x 330 mm

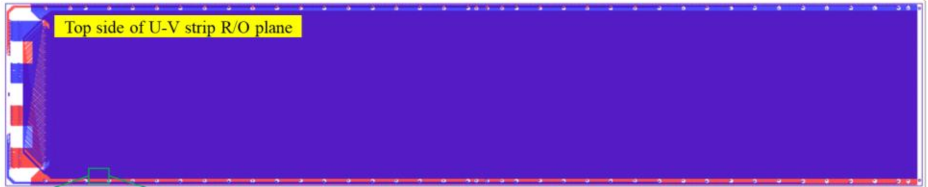


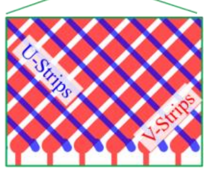
one active segment

Segment's 3-mm boundary

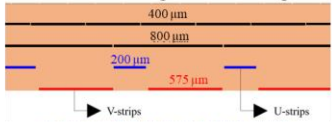
- ❖ The active area of the foil is divided into 6 active segments of area 330 mm × 283 mm separated by 3-mm dead area directly glued to the support frames on top and bottom
- ❖ Each segment is divided into 6 HV sectors (180 mm× 96 mm) separated by 100 µm dead area
  - ❖ The 18 sectors on the left side have normal segmentation
  - ❖ The 18 on the right have a random segmentation ➔ Study impact on detector efficiency
- ❖ Both top and bottom side of the foils are segmented (6 segments of 6 HV sectors each)
- ❖ All 76 HV sectors connections are made on the left side of the GEM foil

Capacitive-sharing U/V strip readout plane Design



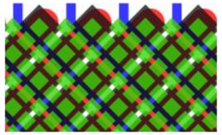


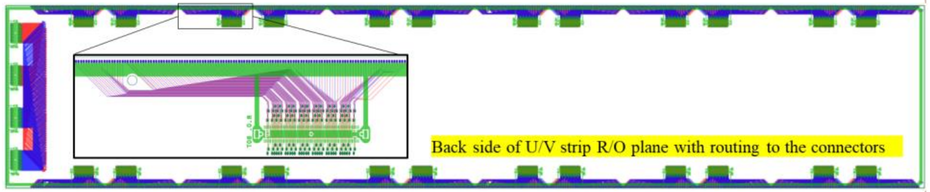
Cross section of capacitive sharing R/O



K. Gnanvo, NIM A1047, 167782 (2023)

2-layers CapaSh structure

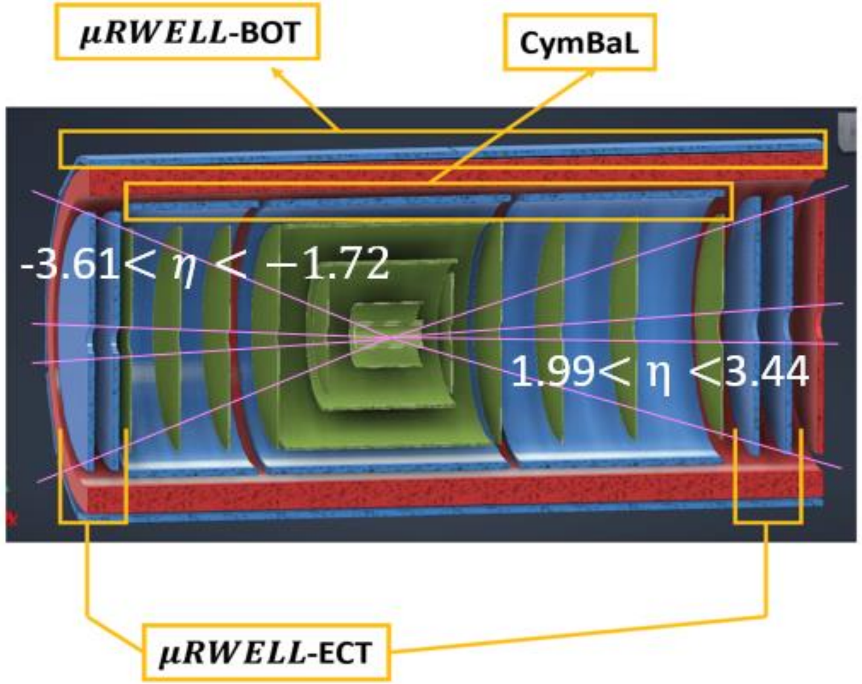




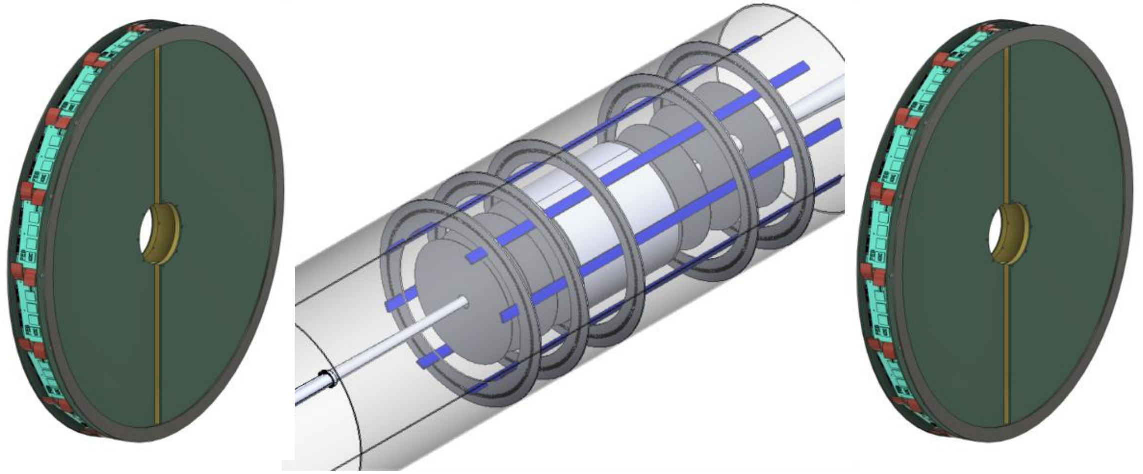
45 degree U / V strips instead of X / Y

- ❖ All connectors at the edge the long side of the detector
- ❖ Pitch = **800 µm** along U / V axis ➔ 1.14 mm along detector edge
- ❖ Strip length = **47 cm** limited strip capacitance concerns
- ❖ Width: top strips (U) = 200 µm and bottom strips (V) = 575 µm
- ❖ 2 layers of capacitive sharing (400 µm and 800 µm) ➔ square pads along U and V axis
- ❖ Total of 3,584 strips ➔ 28 × 140-pins Hirose connectors with 12 ground pins on the back of the PCB

ePIC End Cap Tracker - µRWELL-ECT Disks



Adding **two MPGD Endcap Tracking (ECT) disks** both in the **hadronic** and in the **leptonic regions** increased the number of hits in the |η| > 2 region to improve pattern recognition.



Lepton Disk (LD) µRWELL-ECT

Hadron Disk (HD) µRWELL-ECT

GEM-µRWELL hybrid disks

- Double amplification with hybrid configuration
  ➔ high gain > 10^4
- 2D strip read-out a la "COMPASS"
- 500 - 600 µm pitch guarantees a spatial resolution better than 150 µm
- time resolution ~10 ns

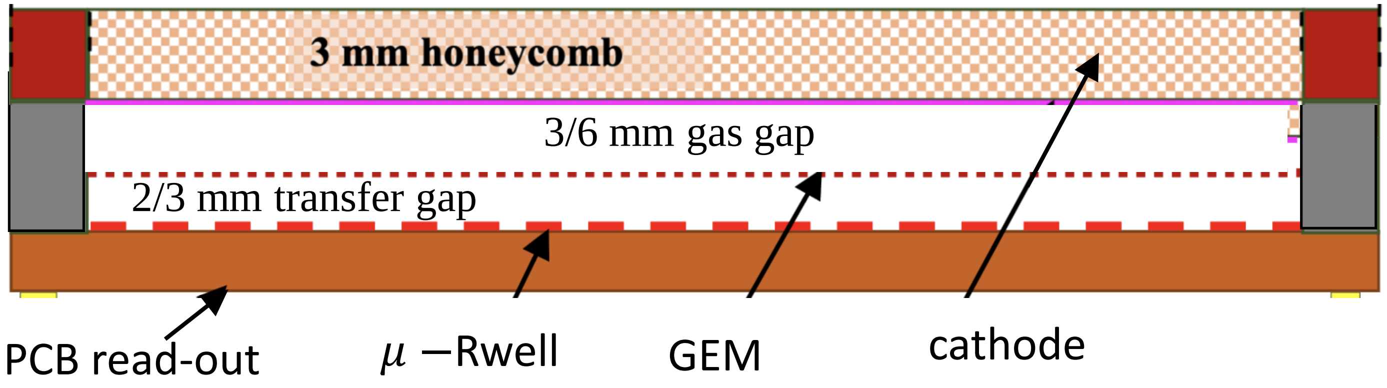
On-detector Front End Boards (FEBs)

- based on SALSA chips

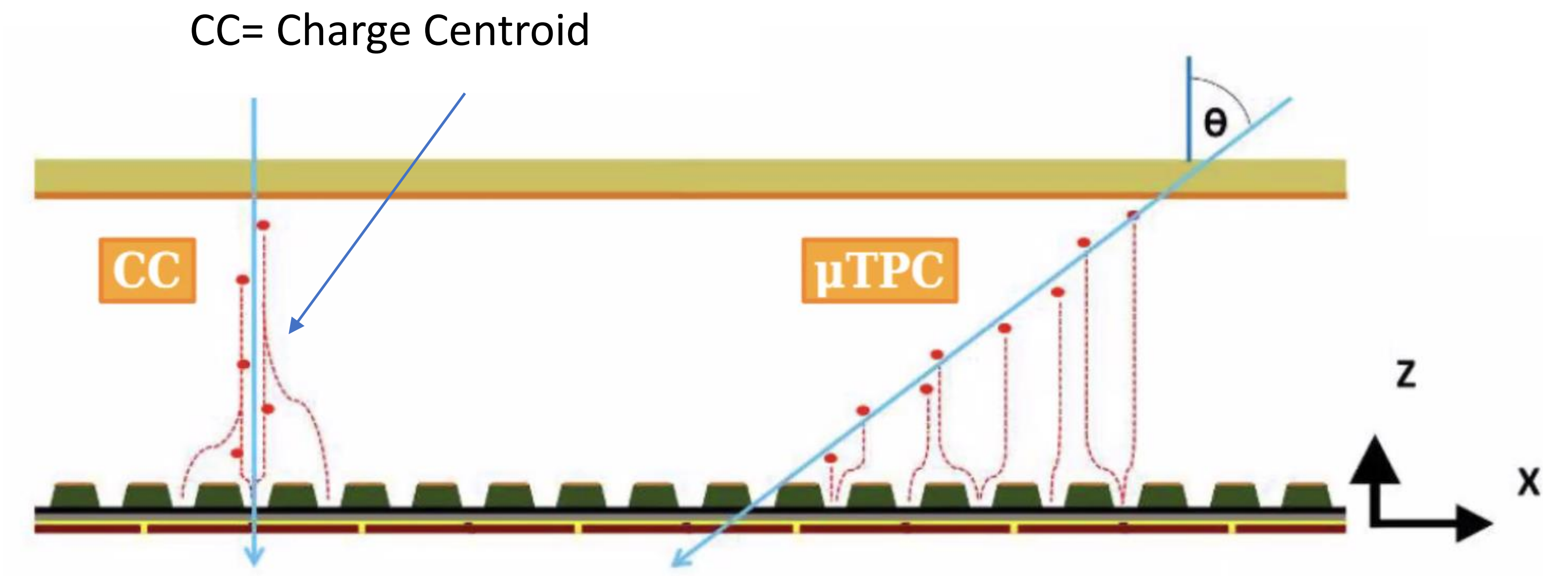
MPGD Disk	Z Pos (cm)	Outer Radius (cm)	Outer Active Reg. radius (cm)	Calculated Beam pipes radii (cm)	Offset (mm)	Inner Radius (cm)	Inner Active Reg. radius (cm)
HD MPGD 2	163.5	50	45	5.58	22.5	9	10.5
HD MPGD 1	150.5	50	45	5.31	19.9	9	10.5
LD MPGD 1	-112.5	50	45	3.77	-3.1	4.5	6.0
LD MPGD 2	-122.5	50	45	3.92	-3.4	4.5	6.0

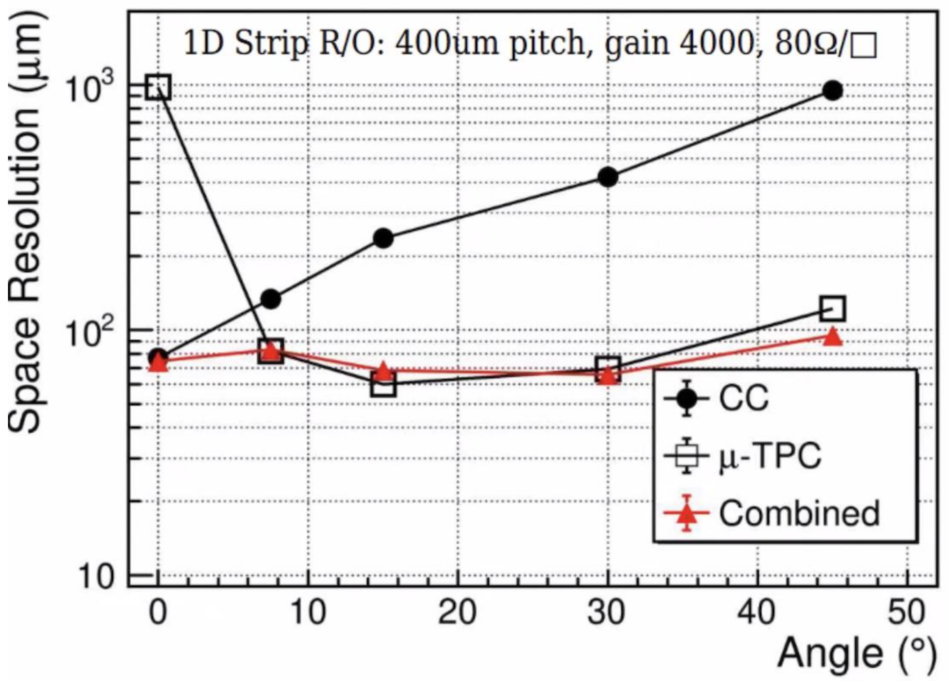
µRWELL-ECT Ongoing R&D: GEM-µRWELL + µTPC

Standard gap GEM-µRWELL hybrid Technology



Combinig the CC and µTPC reconstruction (through a wheighted average) **a resolution well below 100 µm** could be reached over a wide incidence angle range.

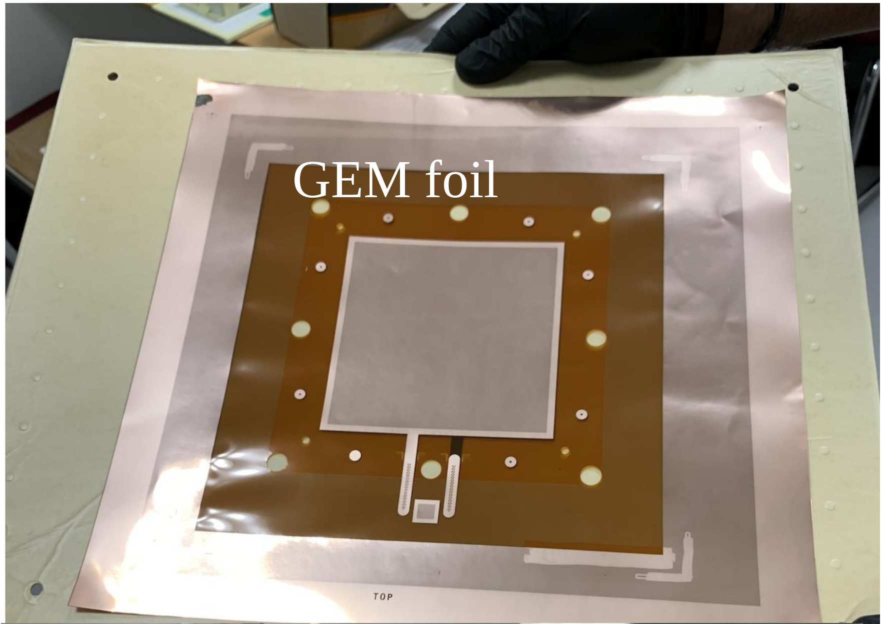


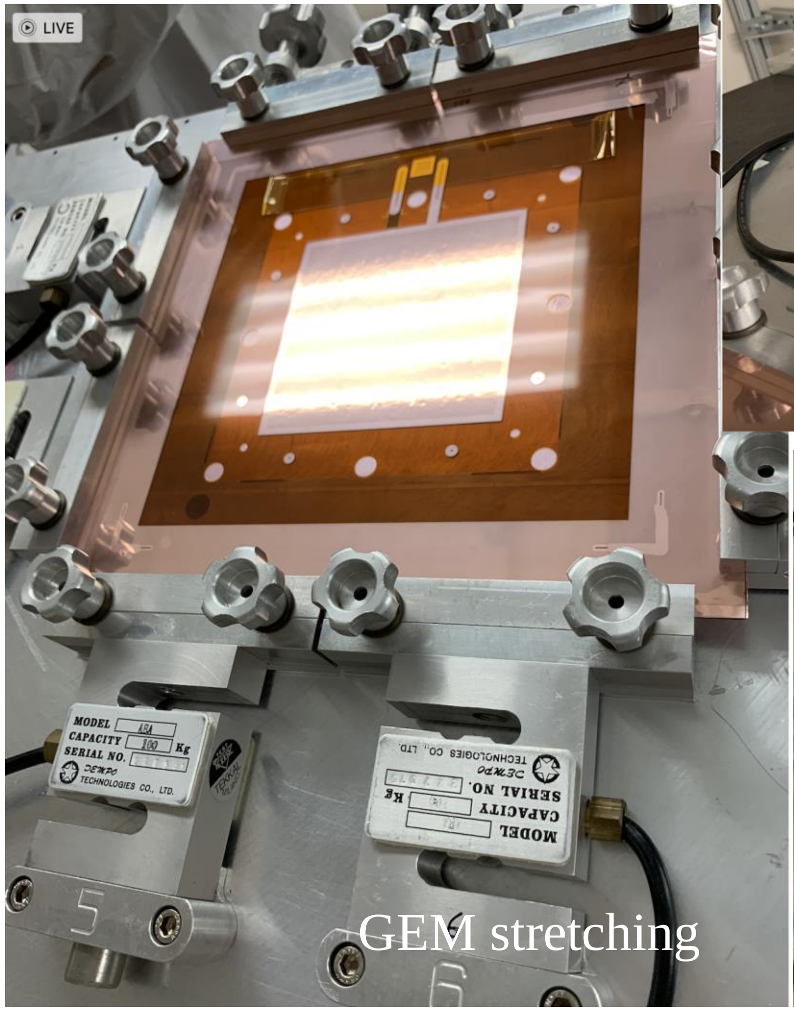


Ongoing test beam effort (Oct / Nov 2024)

µRWELL-ECT Ongoing R&D effort

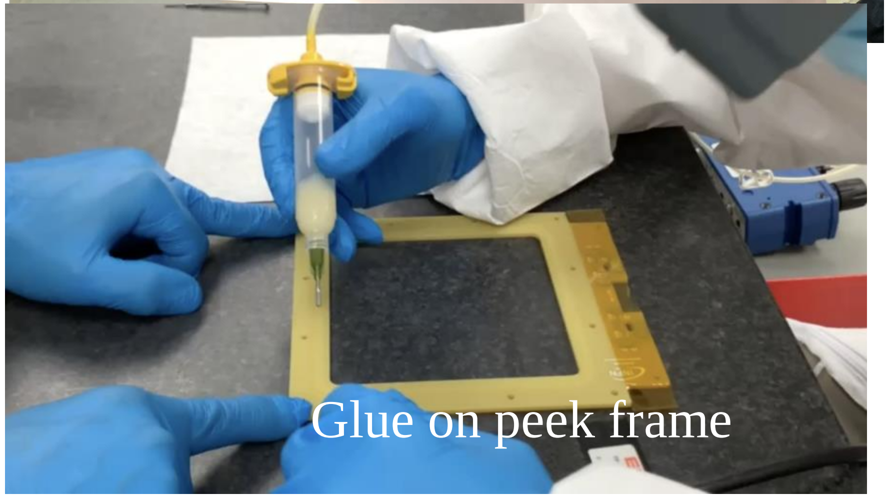
GEM-µRWELL-ECT 10 cm ×10 cm^2 prototypes assembly

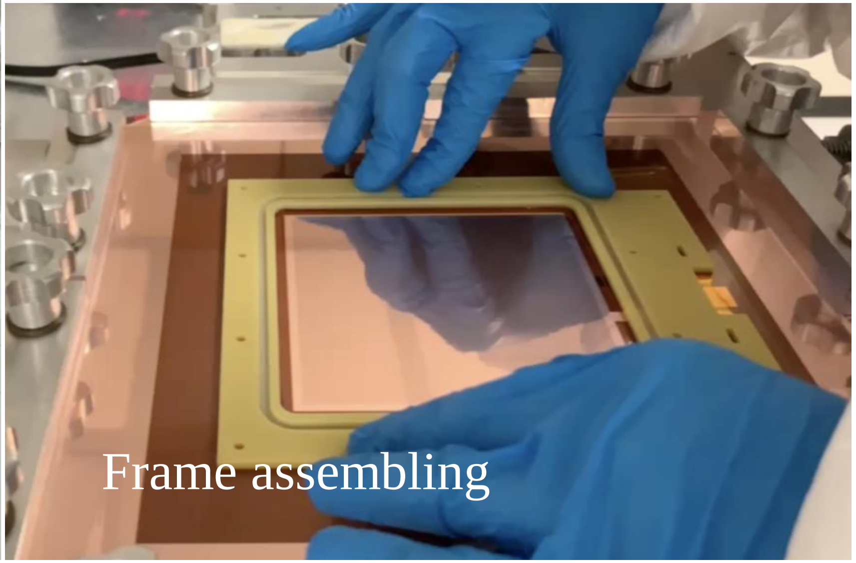

GEM foil



GEM stretching

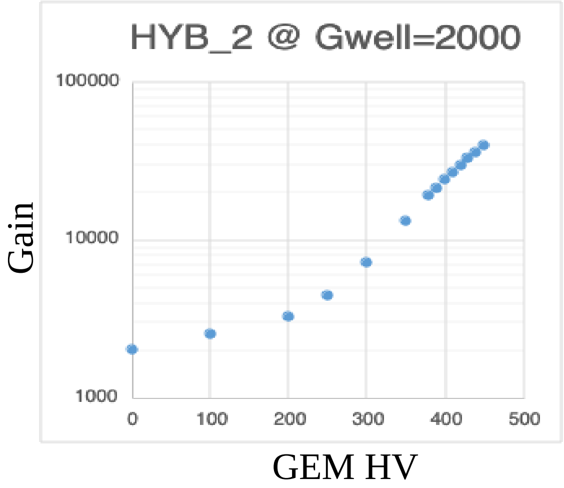

GEM tension measurement

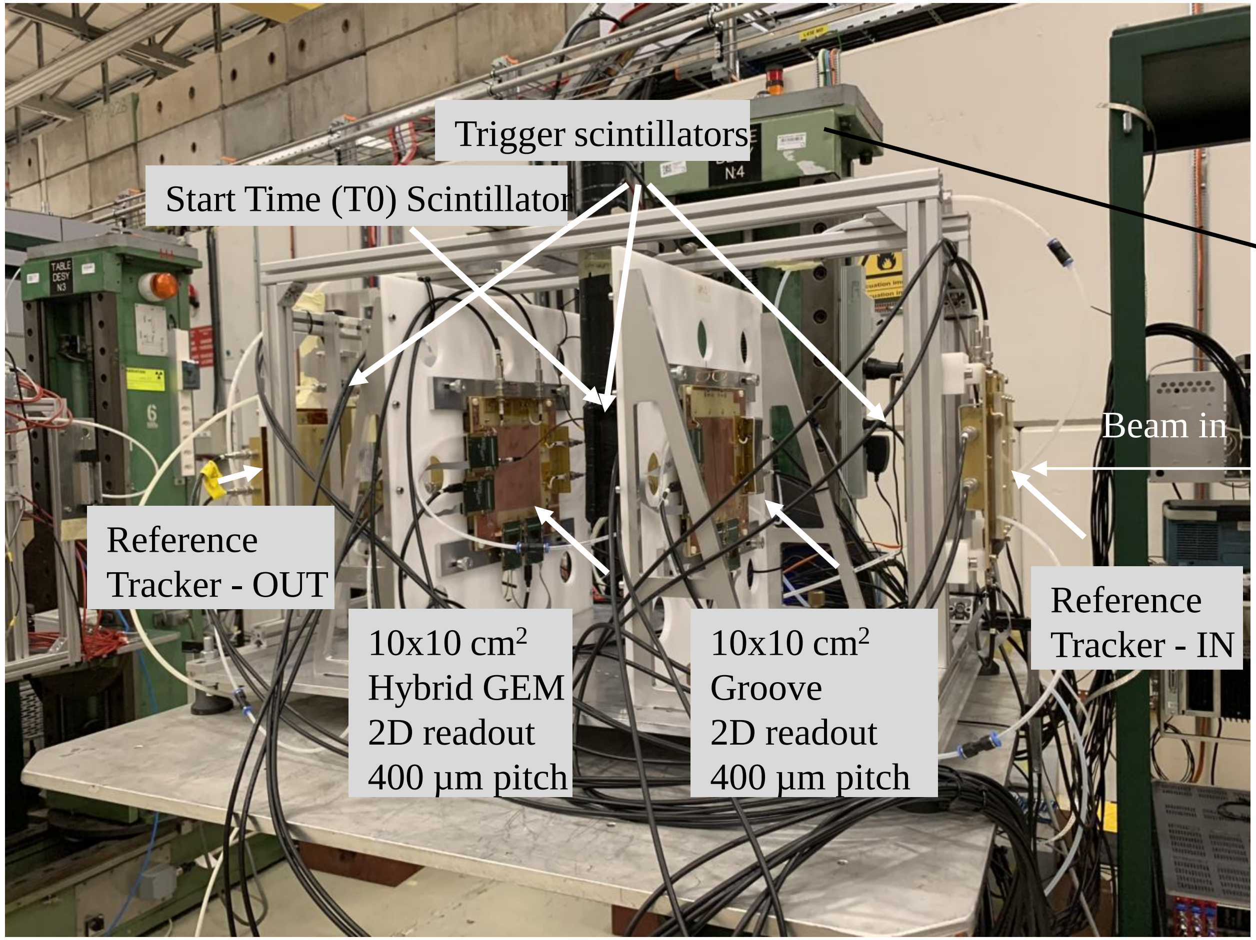

Glue on peek frame


Frame assembling

Ongoing R&D: Test at CERN PS T10 beam line (Nov 2024)

- Reference Trackers: 2 Hybrid GEM-µRWELL with 2D readout
- Detectors Under Test:
  - 2 Hybrid GEM-µRWELL with 2D readout
  - 2 Groove with 2D readout



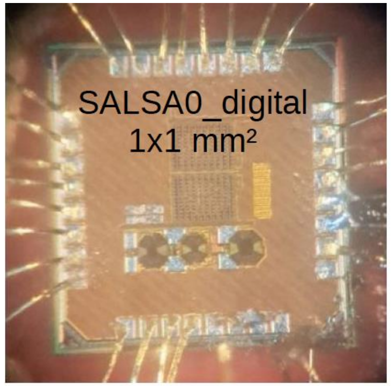


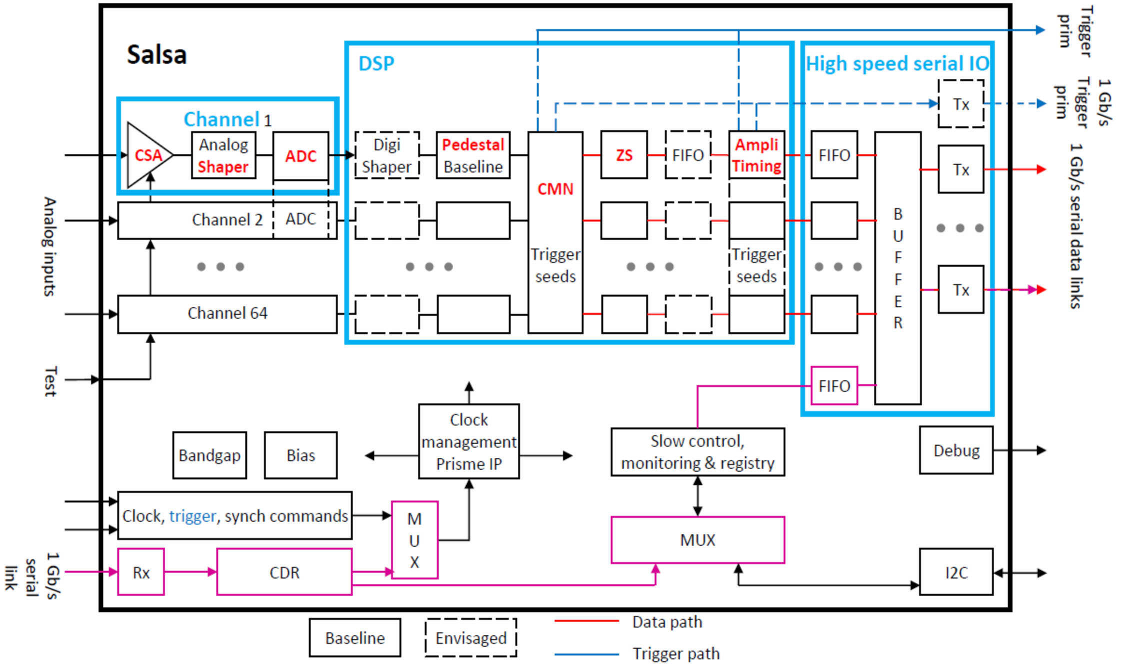
Detectors Under Test may be rotated to study resolution dependence for inclined tracks

ePIC MPGD Electronics: SALSA ASIC

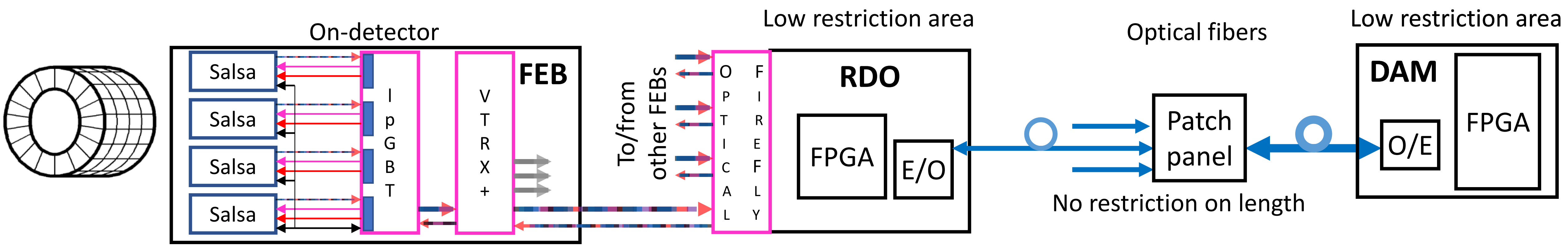
SALSA: New ASIC for ePIC MPGD trackers designed and produced by the CEA Saclay / San Paulo groups

- Channel features
  - → 4 dynamic ranges : 50 fC, 250 fC, 500 fC, 5 pC
  - → 10 peaking times : from 50 ns to 500 ns
  - → Support for high input capacitances up to 1 nF and beyond
  - → Both signal polarities
  - → Rate per channel : up to 100 kHz
  - → Sampling rate : programmable, up to at least 50 MSPS
  - → 12-bit ADC with >10-bit ENOB
- Digital stage programmable features
  - → Pedestal equalization, common mode noise subtraction, zero suppression
  - → Baseline tracking
  - → Signal amplitude and timing extraction
- Clock management with Prisme IP :
  - → Wide range jitter cleaner PLL, 4 clock frequency synthesizer, phase adjustment
- Streaming and triggered readout
  - → Four 1 Gbit/s serial links
  - → Non-ZS, signal shape or time-amplitude readout
- Backend
  - → Traditional interface with separated clock, sync command and control ports
  - → Innovative unified interface over 1 Gbit/s input link
- Implementation
  - → 65 nm TSMC
  - → 10-15 mW/ch @ 1.2V
  - → Radiation hardened : SEU, > 300 Mrad, > 10^{13} n_{eq} / cm^2





SALSA Electronics: Front end board (FEBs) + Optical links



256-channel FEB: On-detector Front End Board (4 SALSA ASICs)

- SALSA receives recovered clock and sync data from an lpGBT eLink group
- SALSA sends physics, calibration and monitoring data to a number of lpGBT lines of the eLink group
- SALSA's are configured over daisy chained I2C interface from lpGBT
- lpGBT provide a bidirectional interface between 4 Salsas and remote FPGA on RDO
- VTRX+ is used with only one T_X line
- All ASICs are radiation hard

1024-channel RDO : common hardware with adaptation based on FireFly transceivers from Samtec

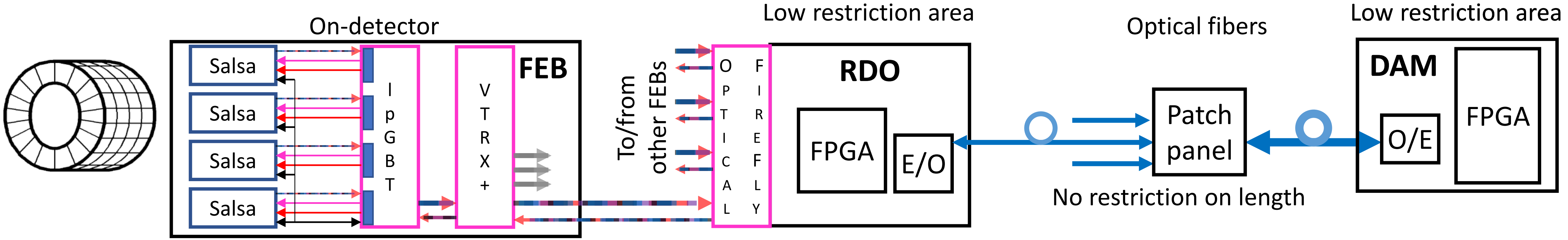
- Single 4-lane bidirectional FireFly is enough to serve 4 FEBs
  - Placed anywhere in user friendly area
- No particular restrictions on power consumption, cooling infrastructure, radiation, magnetic field

Summary

- MPGD tracking detectors in ePIC central region aim at complementing the Si trackers to provide
  - Fast timing (10 ns) for pattern recognition
  - additional space points (< 150 μm) for pattern recognition and help improve angular resolution at the hpDIRC level
- 3 MPGD subsystems in the ePIC Central tracking detectors:
  - CyMBAL and μRWELL-BOT in the barrel regions
  - μRWELL-ECT Disks in the end cap region
- R&D effort for ePIC MPGDs over the past years but is phasing down & replaced by project engineering design (PED) effort
- Development of engineering test articles (pre-production modules) for μRWELL-BOT and μRWELL-ECT modules is on track
- Readout electronics based on the SALSA ASIC under development at CEA Saclay / San Paolo for ePIC MPGD readout

Future looks bright and busy ➔ Design ➔ fabrication ➔ test ➔ commissioning ➔ installation ➔ operation

Back-up



- FEB – frontend board with readout ASICs
  - → Sub-detector specific
- RDO – readout module – first stage of FEB data aggregation, last stage to dispatch clock & control
  - → Common design between sub-detectors, different form factor
- DAM – data aggregation module – interface with computing and global timing and control unit (GTU)
  - → Common design for all sub-detectors
- Downstream towards detector : clock, control, monitoring
- Upstream towards storage : physics, calibration, monitoring data